

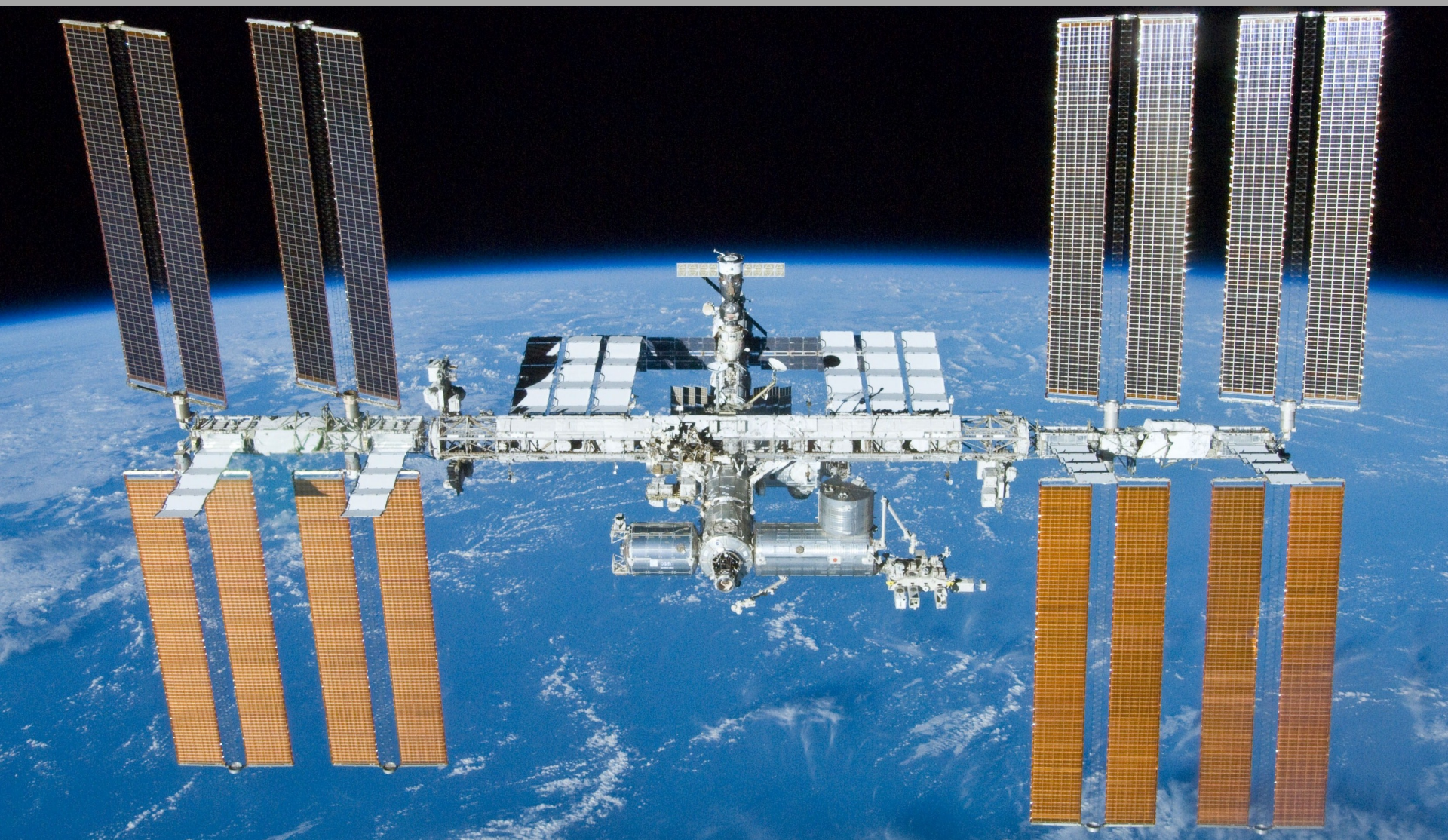
NICER

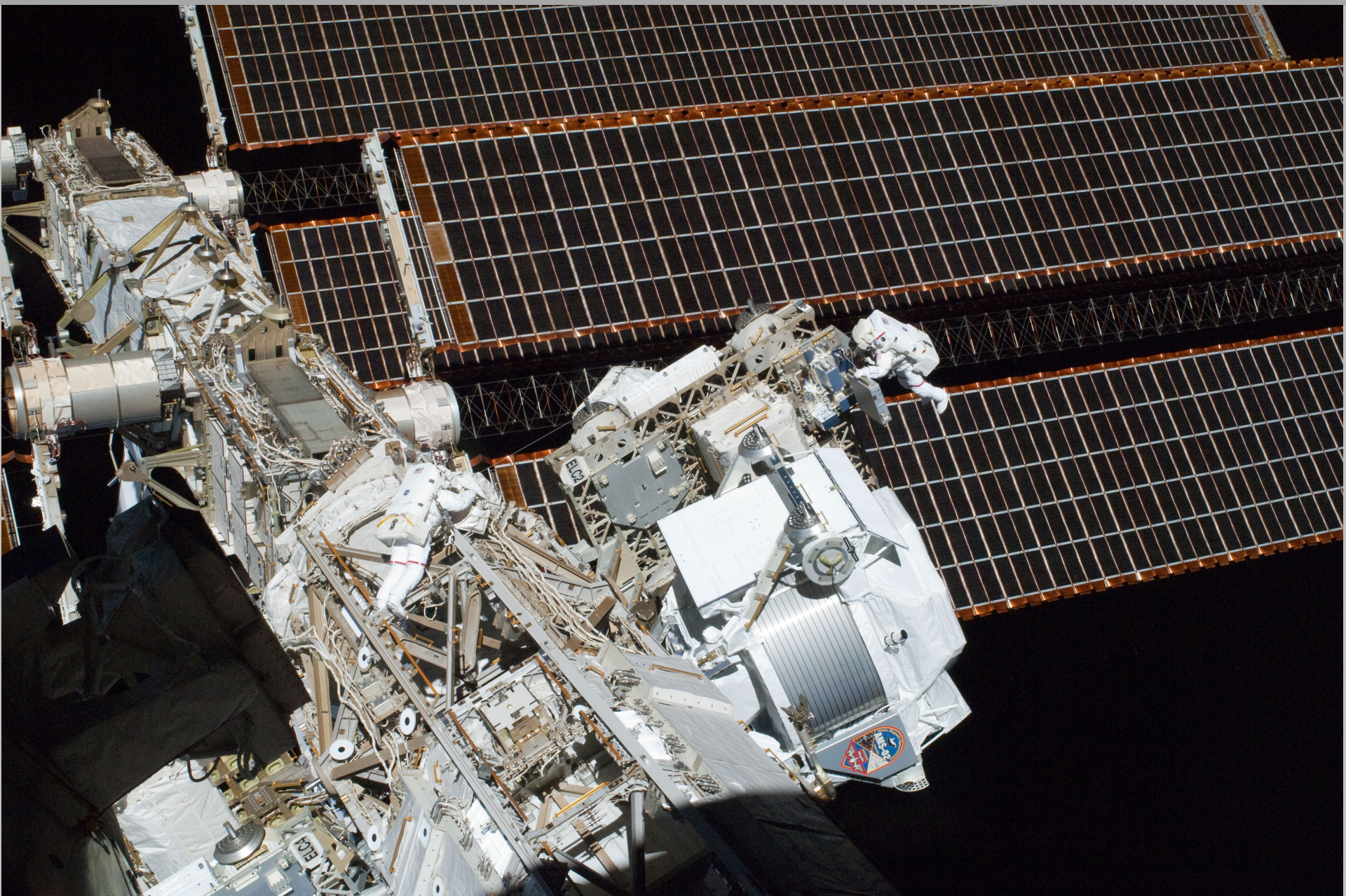
Neutron star Interior Composition Explorer

*A NICER View — Astrophysics
and Exploration from the
International Space Station*

Zaven Arzoumanian

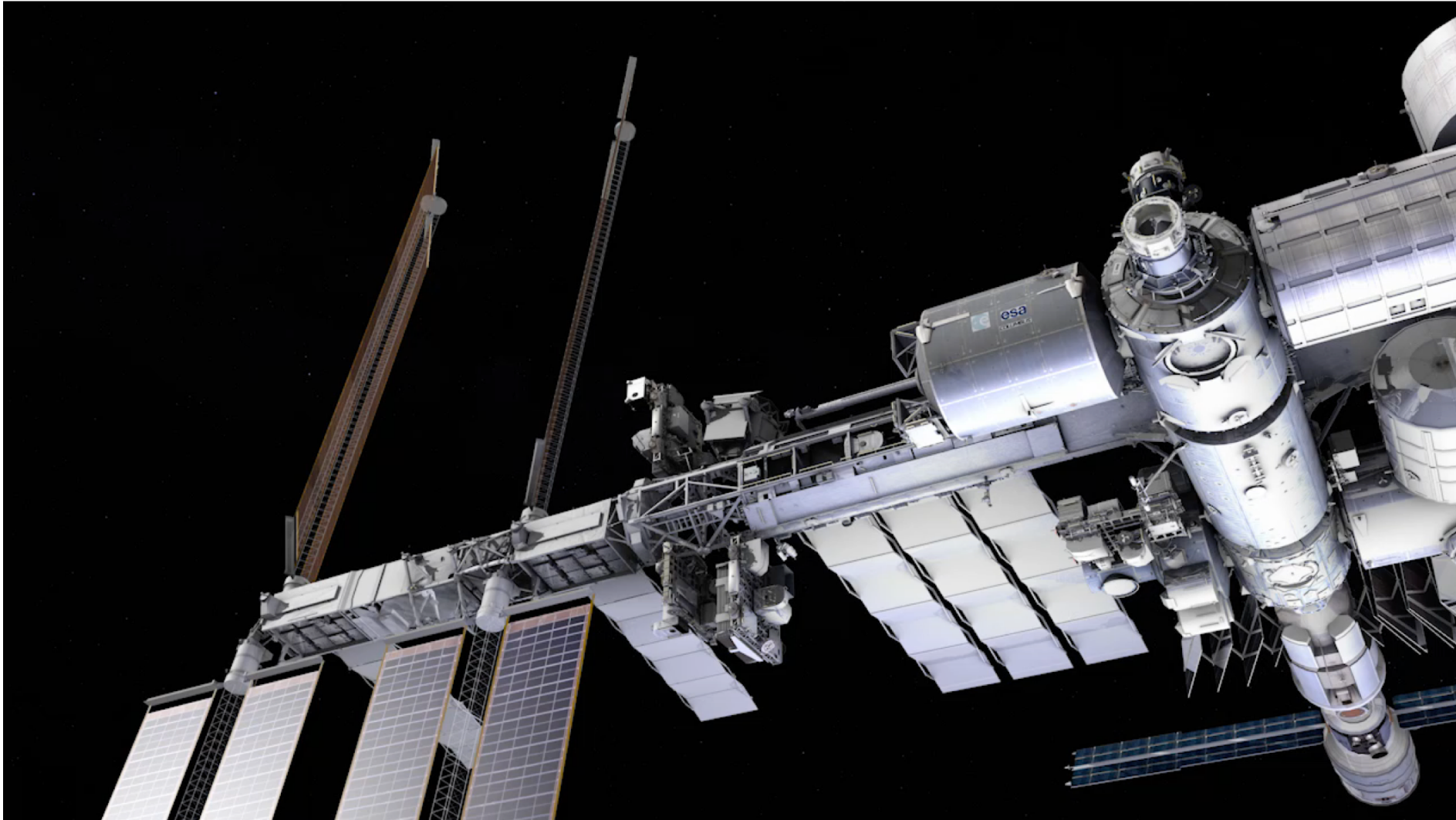








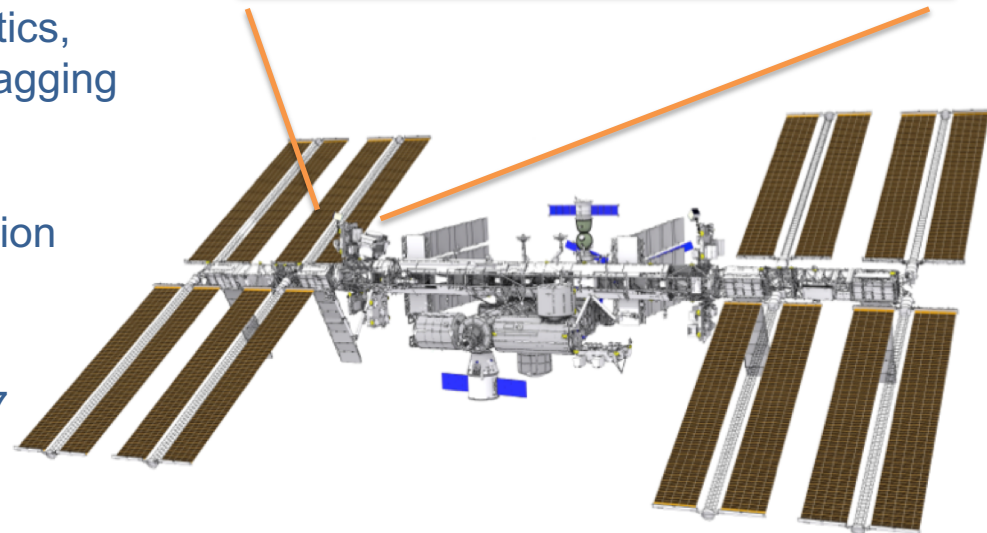
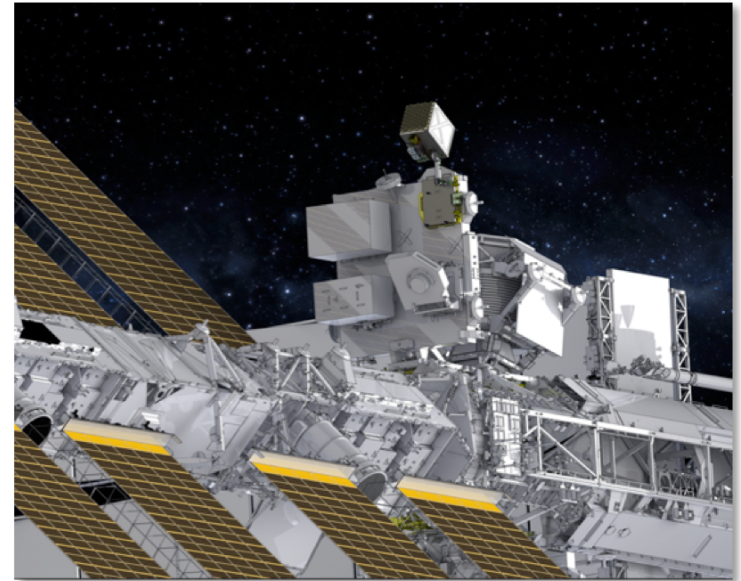
NICER at home on ISS





NICER/SEXTANT — Overview

- **PI:** Keith Gendreau, NASA GSFC
- **Science:** Neutron star **structure**, **dynamics**, & **energetics** through soft X-ray timing spectroscopy
- **Launched:** June 3, 2017, SpaceX-11 resupply
- **Platform:** ISS external attached payload with active pointing
- **Duration:** 18 months baseline science mission; likely **GO extension**
- **Instrument:** 0.2–12 keV “concentrator” optics, silicon-drift detectors, GPS absolute time tagging and position
- **Enhancements:**
 - Demonstration of pulsar-based navigation
 - PI discretionary & ToO time
- **Status:**
 - Commissioning complete 17 July, 2017
 - Baseline science mission in progress



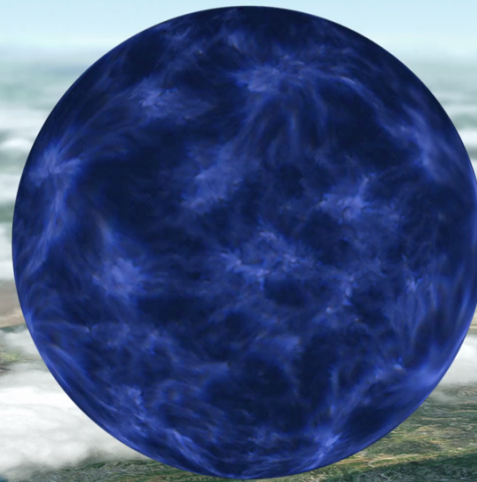


Outline

- Science
 - Why neutron stars?
 - NICER's objectives
 - Focus on key science: modeling X-ray emissions
 - Early NICER results
 - Guest Observer plans
- The NICER payload
 - Design and performance
 - Launch and installation
- SEXTANT
 - History
 - Method and objectives



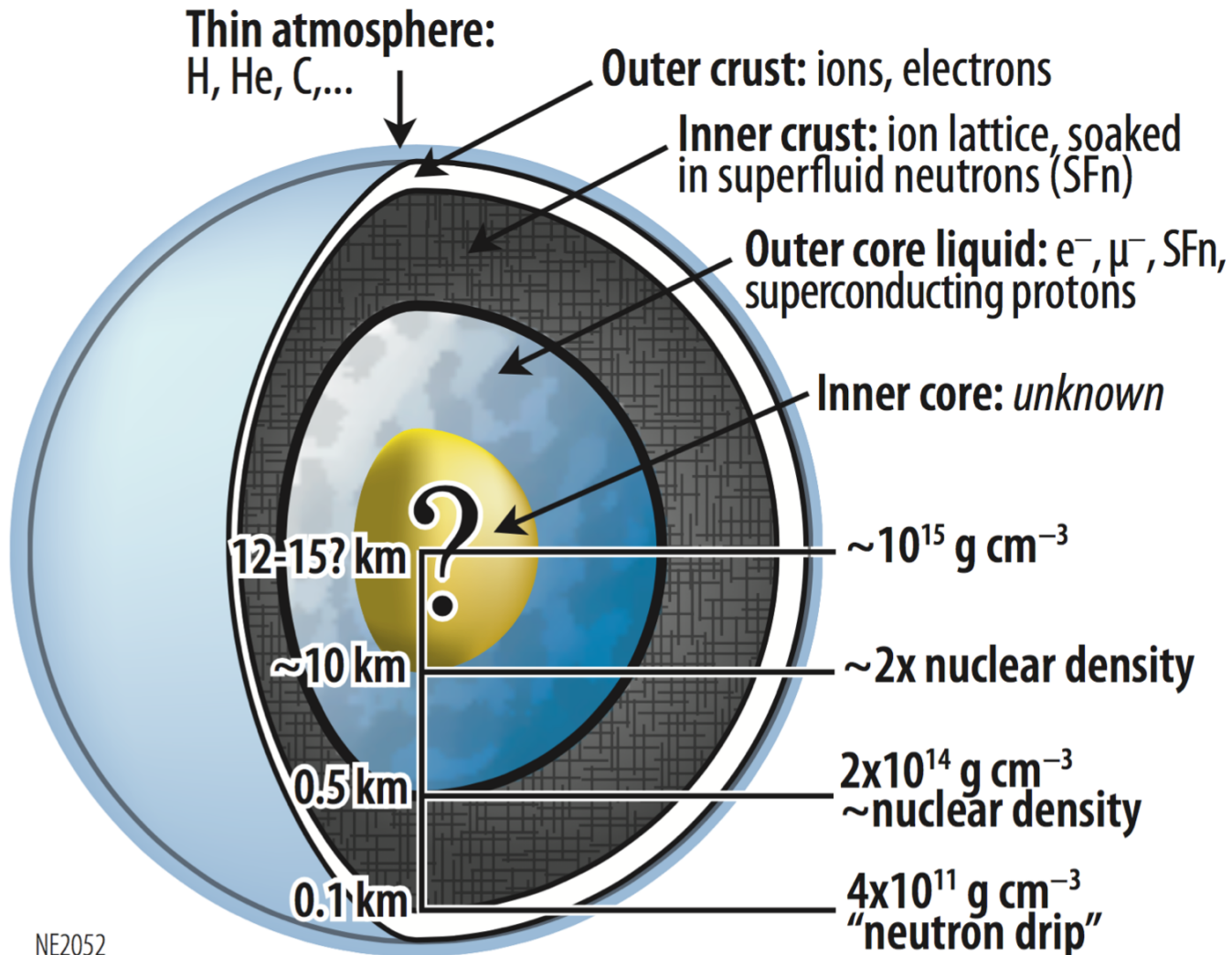
Why neutron stars?





Why neutron stars? (cont.)

An 80-year-old question mark



NE2052

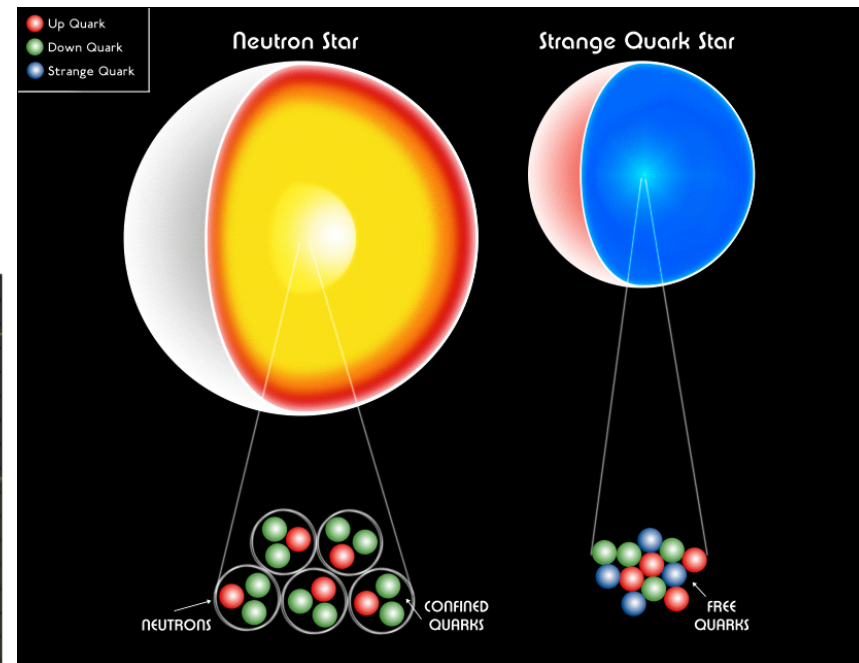
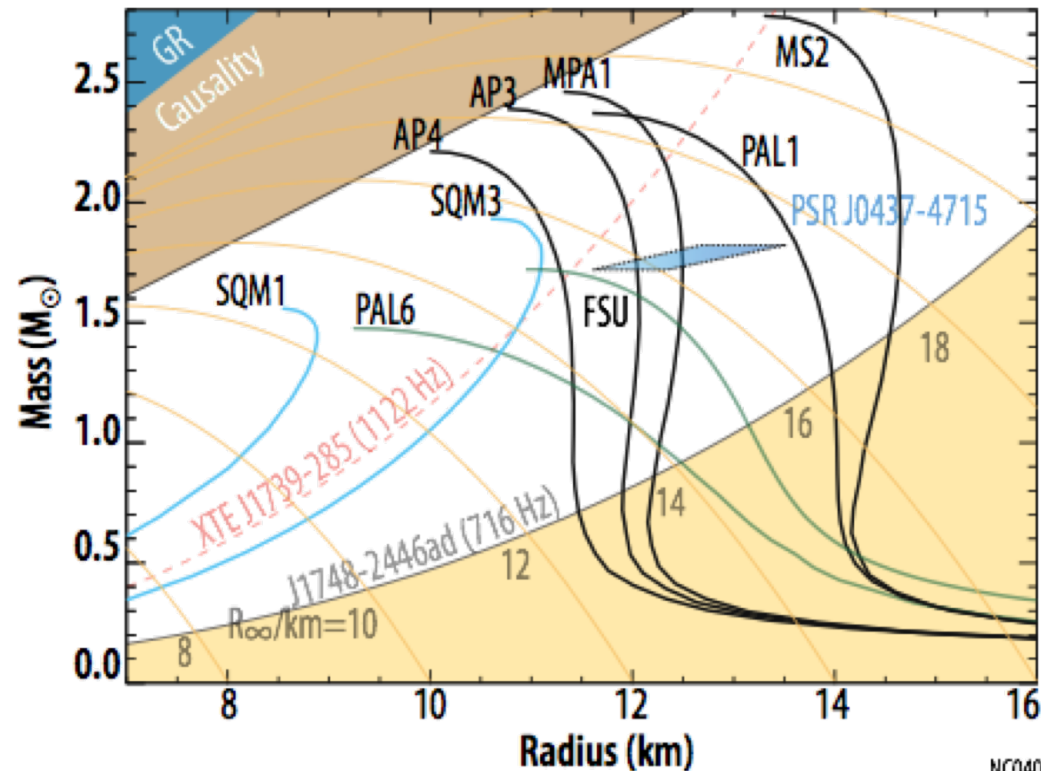


Science objectives

I — Neutron star structure

Radius and mass reveal interior composition

| Objective | Measurements |
|--|--|
| Structure — Uncover nature of matter within neutron stars | Neutron star radii, masses, & cooling timescales |



Simulations show $\pm 5\%$ M - R contours with $\sim 10^6$ photons through modeling of gravitationally altered pulse lightcurves

Need just 3 objects (Psaltis & Ozel 2009, Phys Rev D 80, 103003).

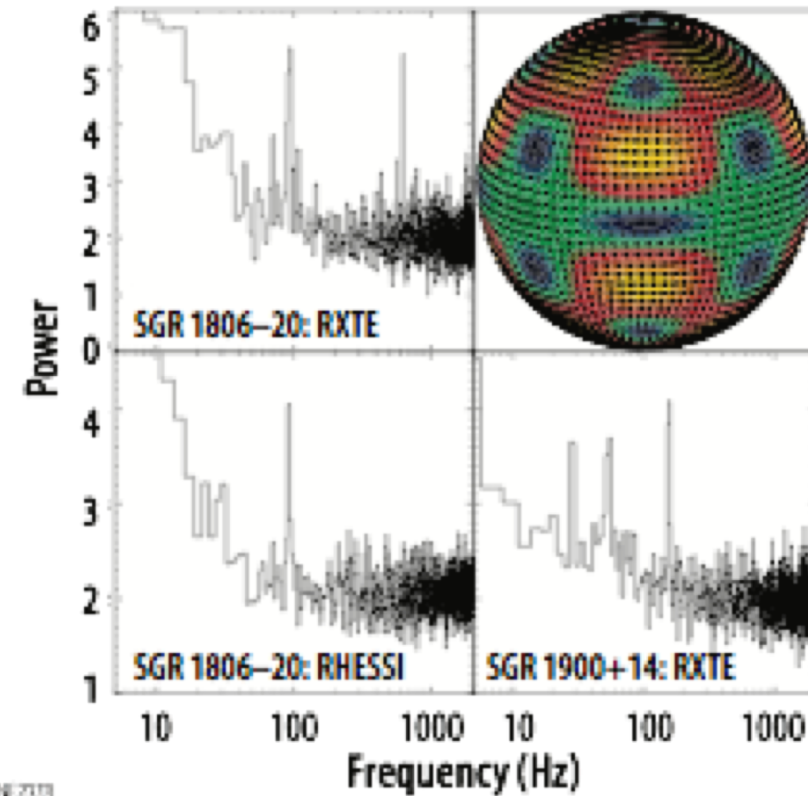
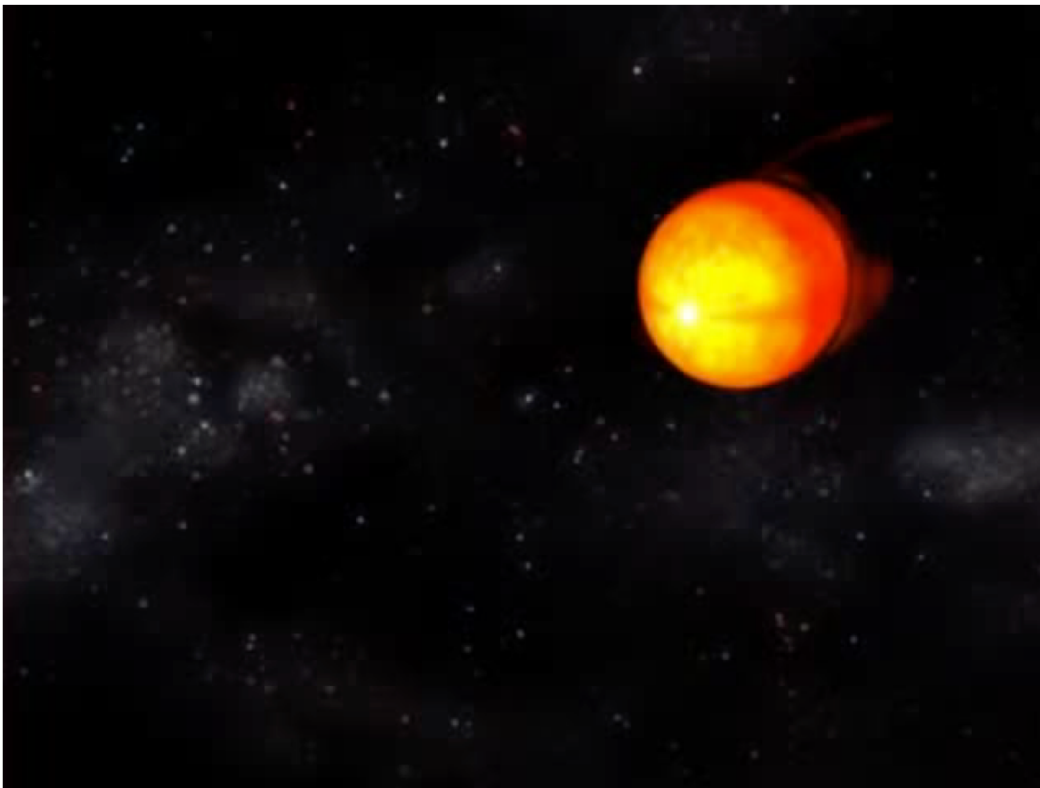


Science objectives

II — Neutron star dynamics

Spin, accretion, and “starquake” phenomena probe crustal physics and external interactions

| Objective | Measurements |
|--|---|
| Dynamics — Reveal physics of variability on many timescales | Rotational stability, outbursts, oscillations, and precession |



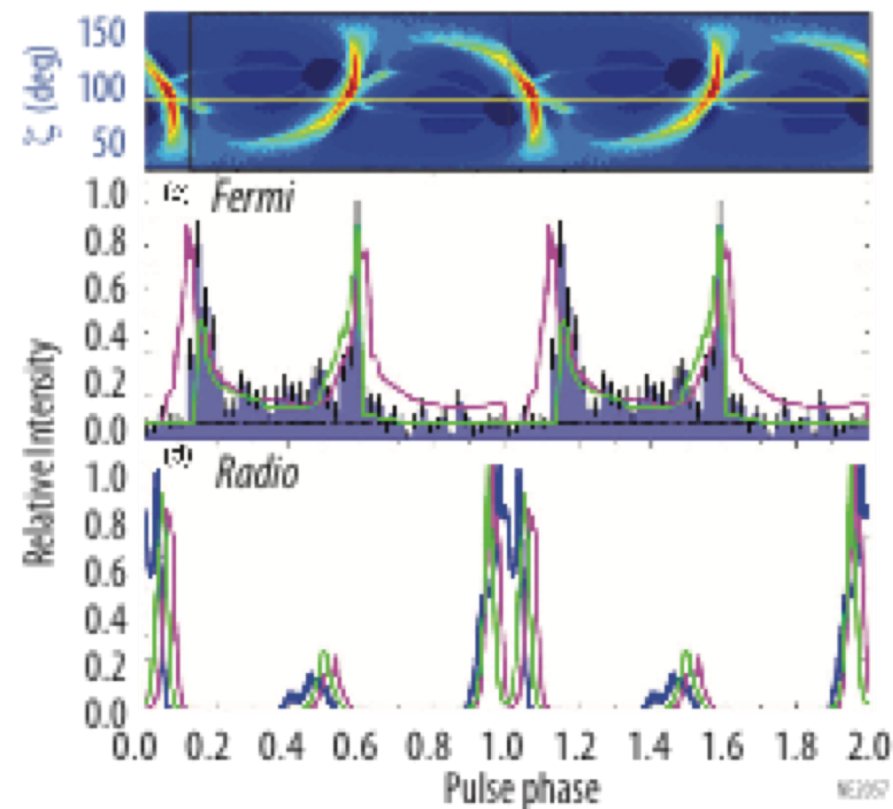
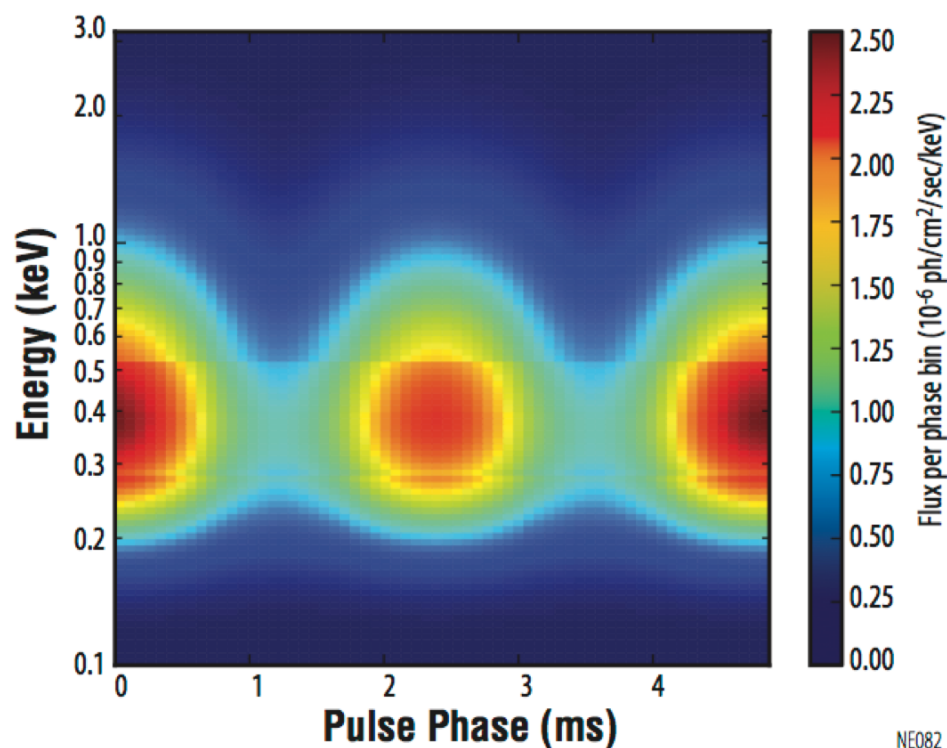


Science objectives

III — Neutron star energetics

Sites & mechanisms of radiation reveal thermal, magnetic, nuclear, etc., energy stores

| Objective | Measurements |
|--|---|
| Energetics — Determine where energy is stored and extracted | Intrinsic radiation patterns, spectra, and luminosities |

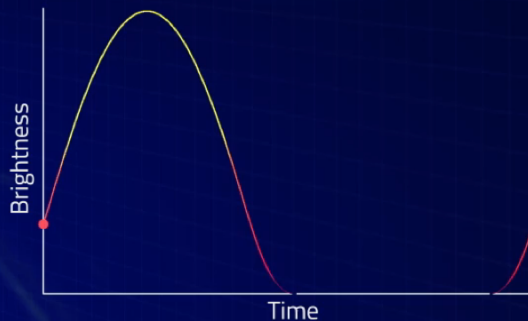
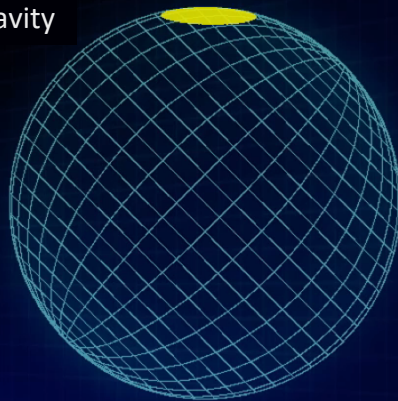




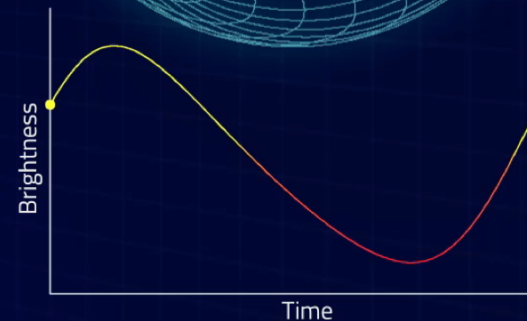
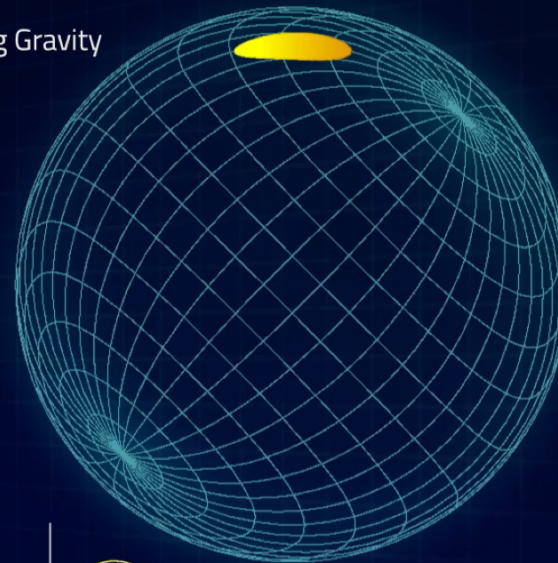
Modeling surface emission to infer M - R

Gravitational light-bending saves the day!

Weak Gravity

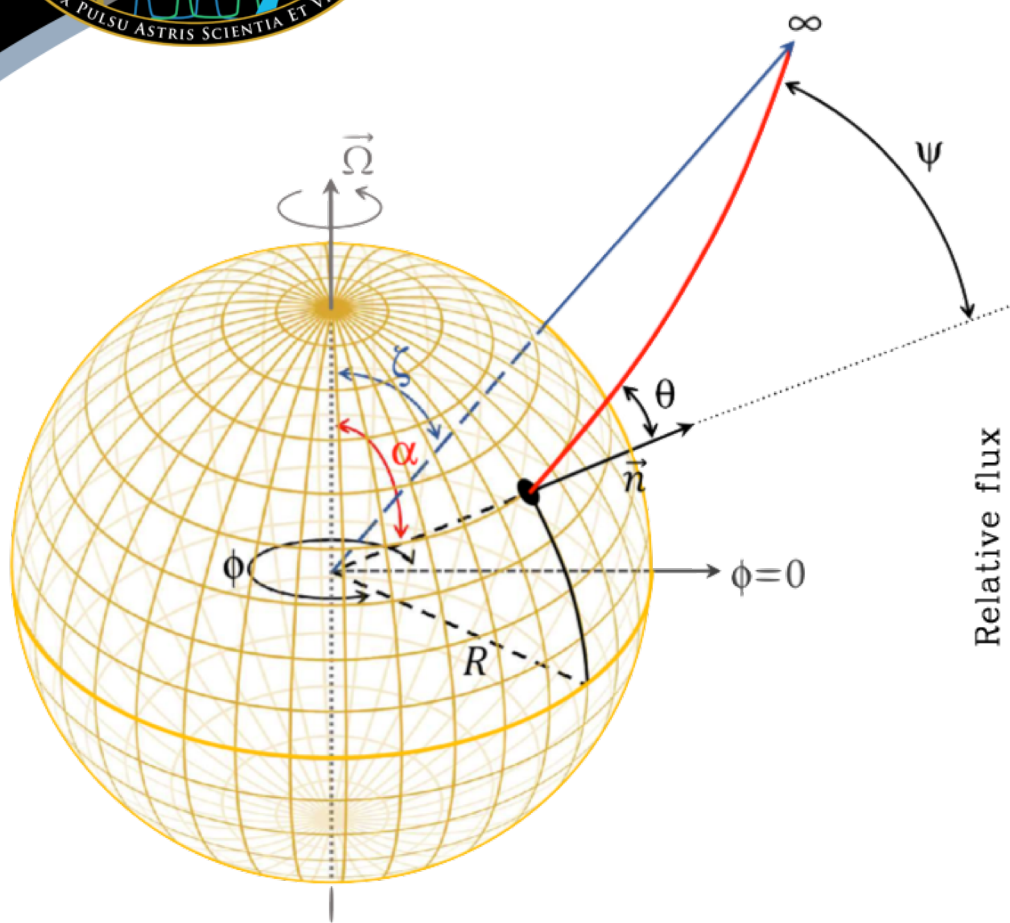


Strong Gravity

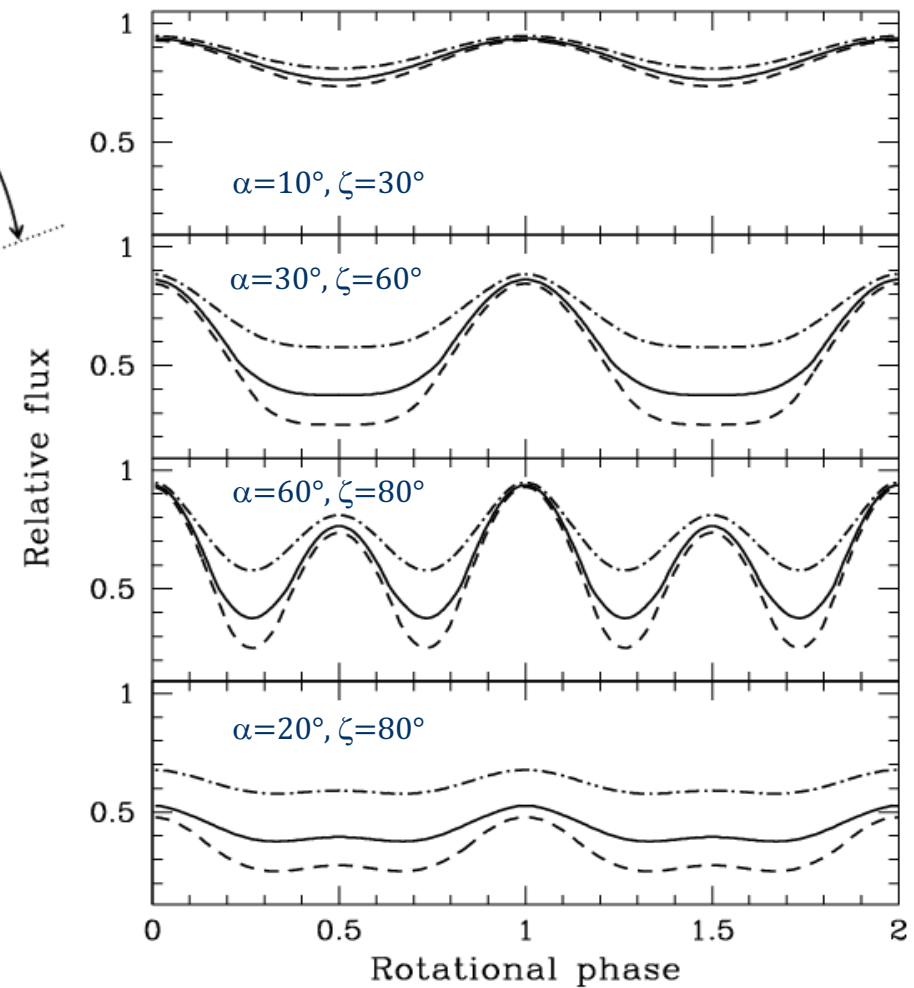




Inferring neutron star radii through lightcurve modeling — geometry



Bogdanov, Rybicki, & Grindlay, *ApJ*, 670, 668 (2007)



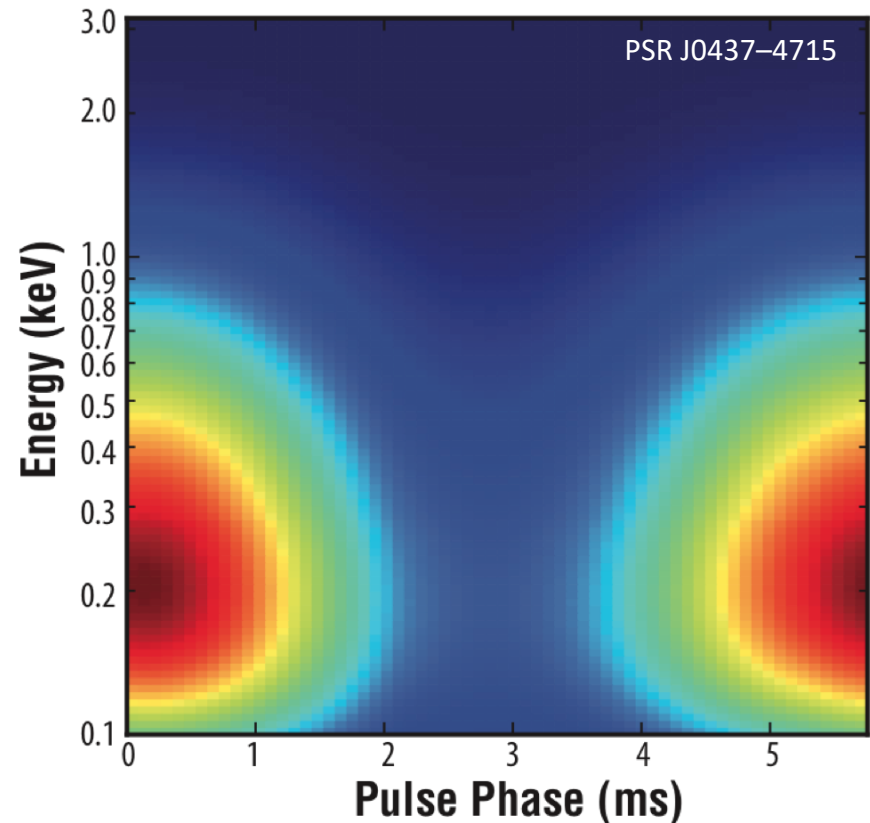
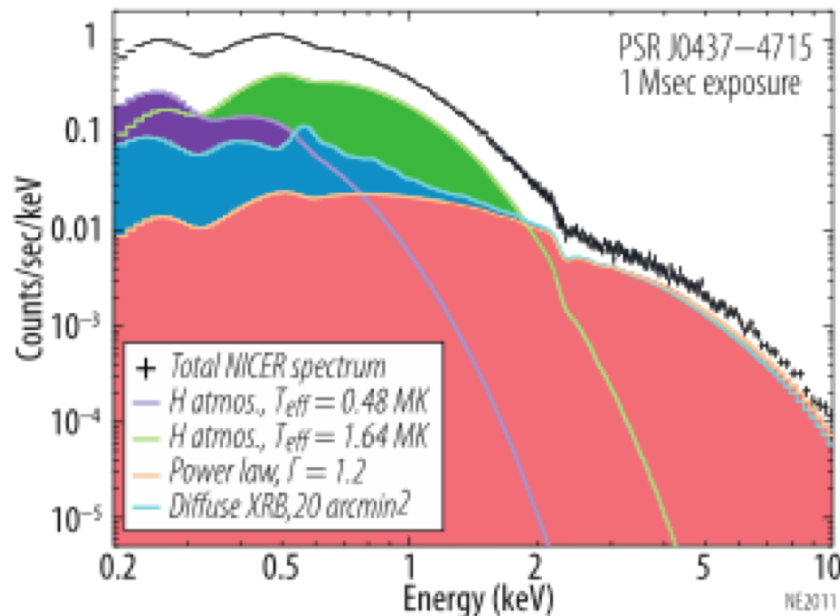
- . - . 9 km
 ————— 12 km
 - - - - - 16 km

for $M = 1.4 M_\odot$



Inferring neutron star radii through lightcurve modeling — spectroscopy

- NICER is most sensitive where neutron stars are brightest: $\sim 10^6$ K thermal emission peaks in soft X-rays
- Energy resolution enables phase-resolved spectroscopy



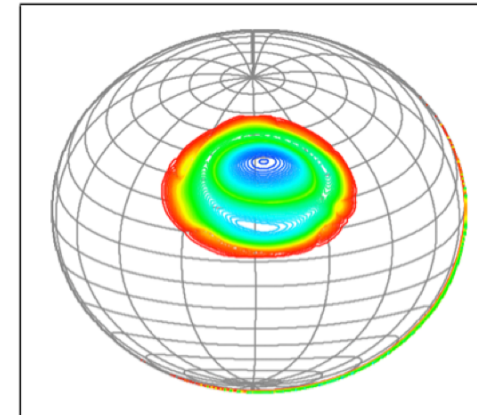
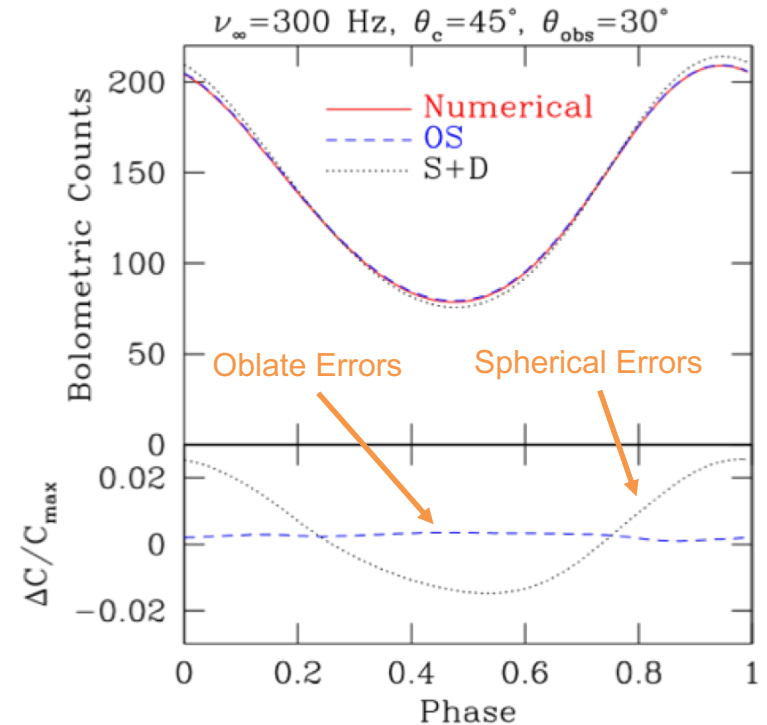
- Absolute time resolution enables coherent light curve integration over years



Potential sources of systematics

Known unknowns...

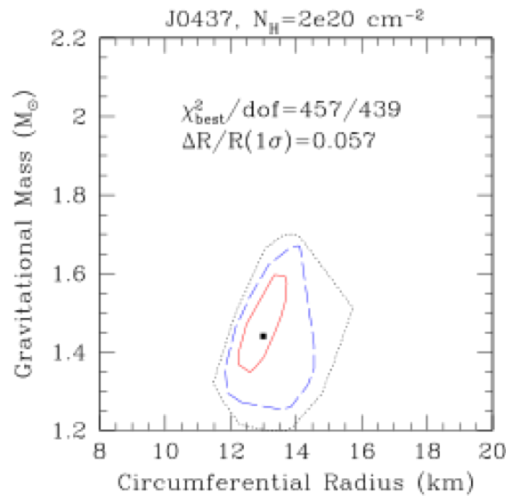
- Uncertainties in model
 - ✓ GR calculations (approximations & numerical accuracy)
 - ✓ Atmosphere model (depth of heating, hydrogen vs. helium, fully ionized?)
- Instrument calibration
 - ✓ Method *does not depend on absolute flux determination*
- X-ray background
 - ✓ How accurately must the background be measured?
- Unknown or weakly constrained properties of neutron star
 - ✓ Polar cap size/shape and heat distribution
 - ✓ Non-thermal emission (pulsed or unplugged?)
 - Magnetic inclination and viewing angle
 - Mass



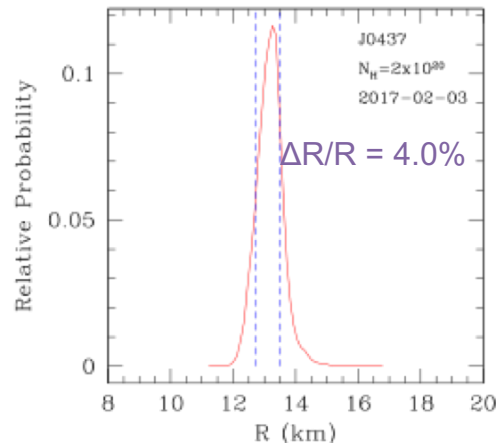


Lightcurve modeling sim results

PSR J0437-4715, sim. $T_{\text{exp}} = 1$ Msec

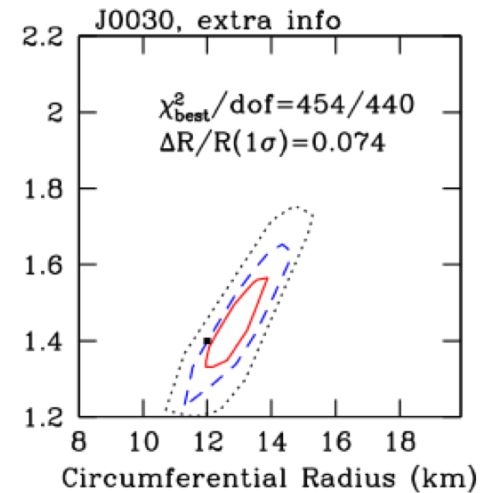


Mass known
to $\pm 5\%$

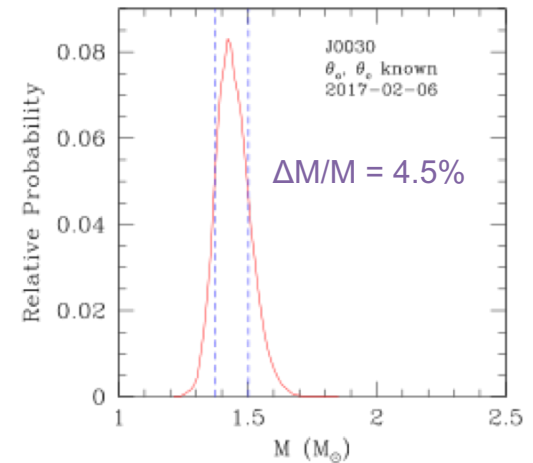
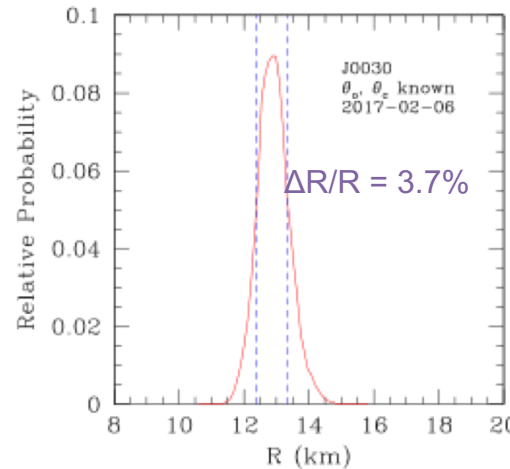


$\pm 5\%$ in R achieved in < 1 Msec

PSR J0030+0451, sim. $T_{\text{exp}} = 3$ Msec



Possible first-
ever mass of
isolated
neutron star

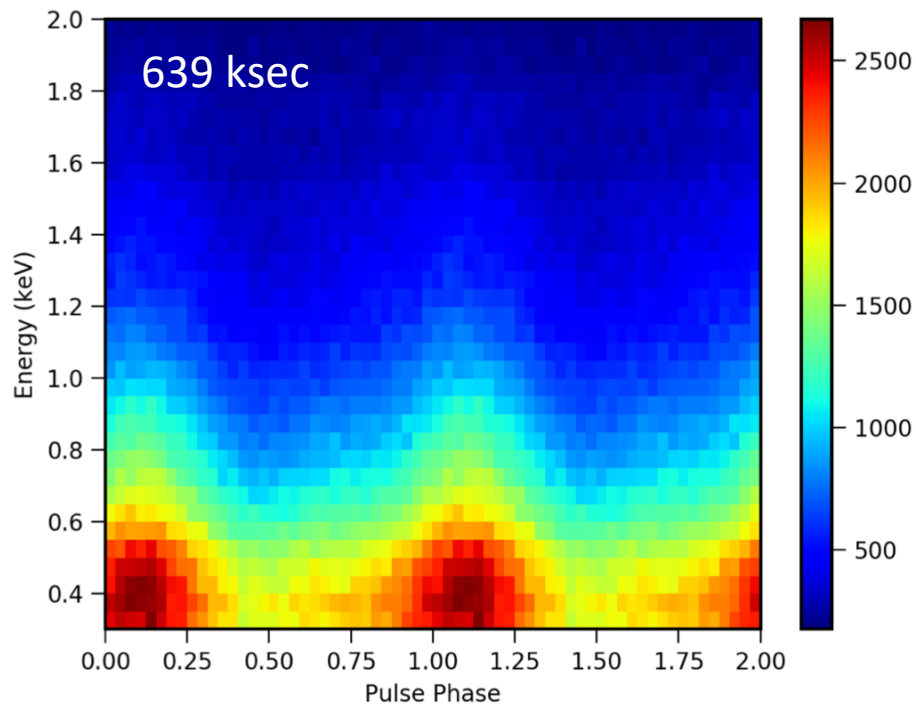


$\pm 5\%$ uncertainty in R achieved in 1.6 Msec

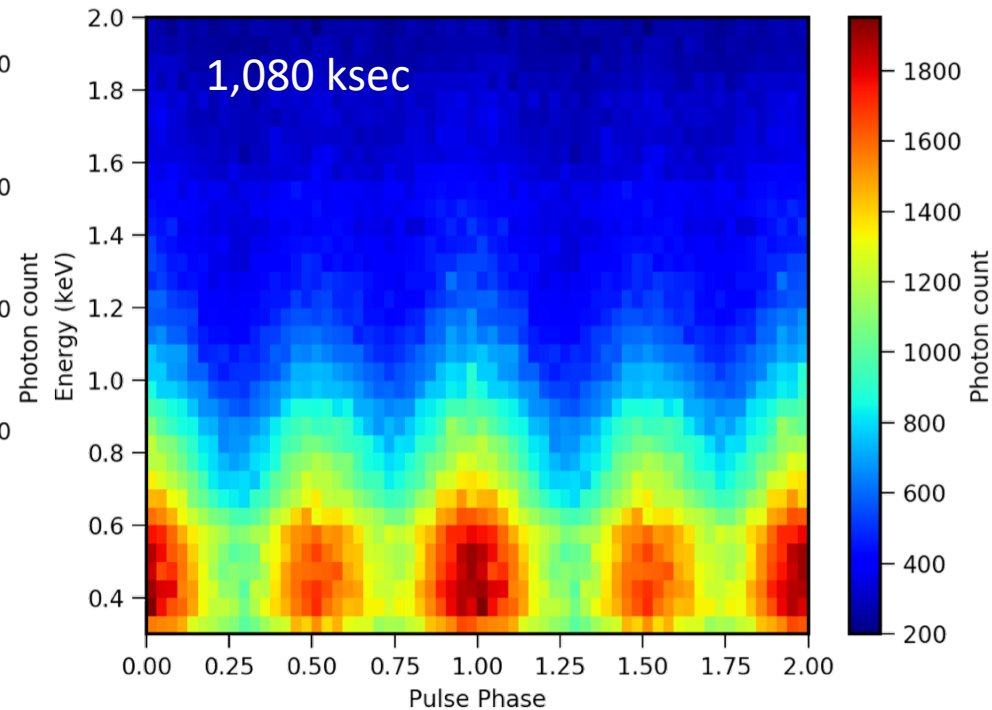


NICER lightcurves (cont.)

PSR J0437–4715



PSR J0030+0451



At pulse peaks, thousands of photons in joint spectral and pulse-phase bins.

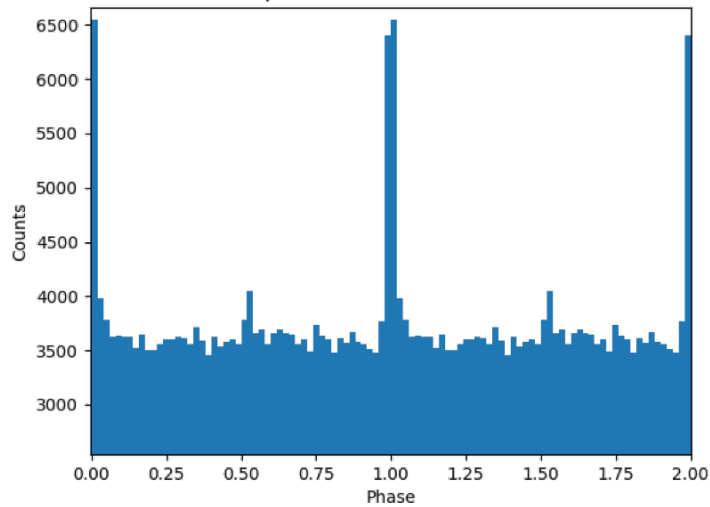


NICER timing results

MSPs with exceptionally high timing precision

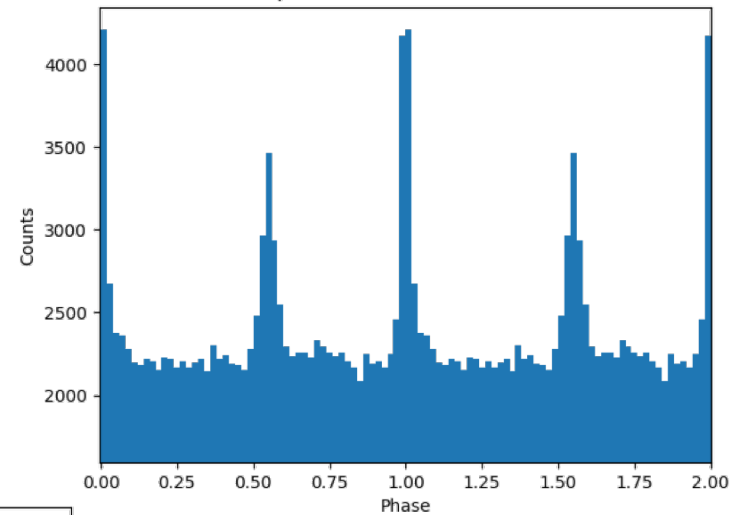
PSR_B1937+21

Total exposure: 294936 s Counts/s: 0.63



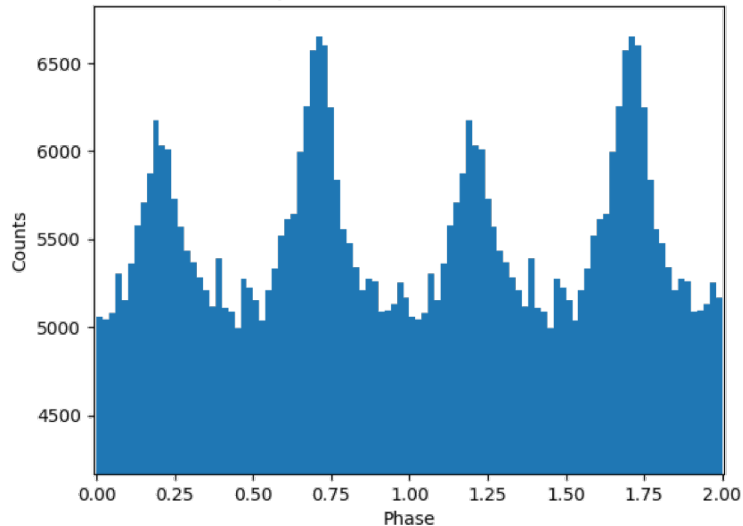
PSR_B1821-24

Total exposure: 140150 s Counts/s: 0.85



PSR_J0218+4232

Total exposure: 353000 s Counts/s: 0.78





Two recent Astronomer's Telegrams

Re-detection of the accreting pulsar in Swift J1756.9–2508

NICER Detects Pulsations from Swift J1756.9-2508

ATel #11502; *P. M. Bult, K. C. Gendreau (NASA/GSFC), P. S. Ray (NRL), D. Altamirano (Univ. of Southampton), Z. Arzoumanian (NASA/GSFC), D. Chakrabarty (MIT), S. Guillot (IRAP, CNES), G. K. Jaisawal (DTU Space), R. M. Ludlam (Univ. of Michigan), C. B. Markwardt (NASA/GSFC), I. A. Mereminskiy (Space Research Institute, Moscow), F. Ozel (Univ. of Arizona), A. Sanna (UNICA), T. E. Strohmayer (NASA/GSFC), M. T. Wolff (NRL)*
on 5 Apr 2018; 02:58 UT

Credential Certification: Deepto Chakrabarty (deepto@space.mit.edu)

Subjects: X-ray, Neutron Star, Transient, Pulsar

Referred to by ATel #: [11505](#), [11523](#)

[Tweet](#)

Following the report of a new outburst of the accreting millisecond X-ray pulsar Swift J1756.9-2508 (ATel #11497), NICER performed pointed observations starting on 2018 April 3, collecting 9.4 ks of exposure over the ~30 hours between April 3 15:18 UTC and April 4 21:01 UTC. A source is clearly detected at ~30 ct/s (1-10 keV); the background level in this band is less than 1 ct/s.

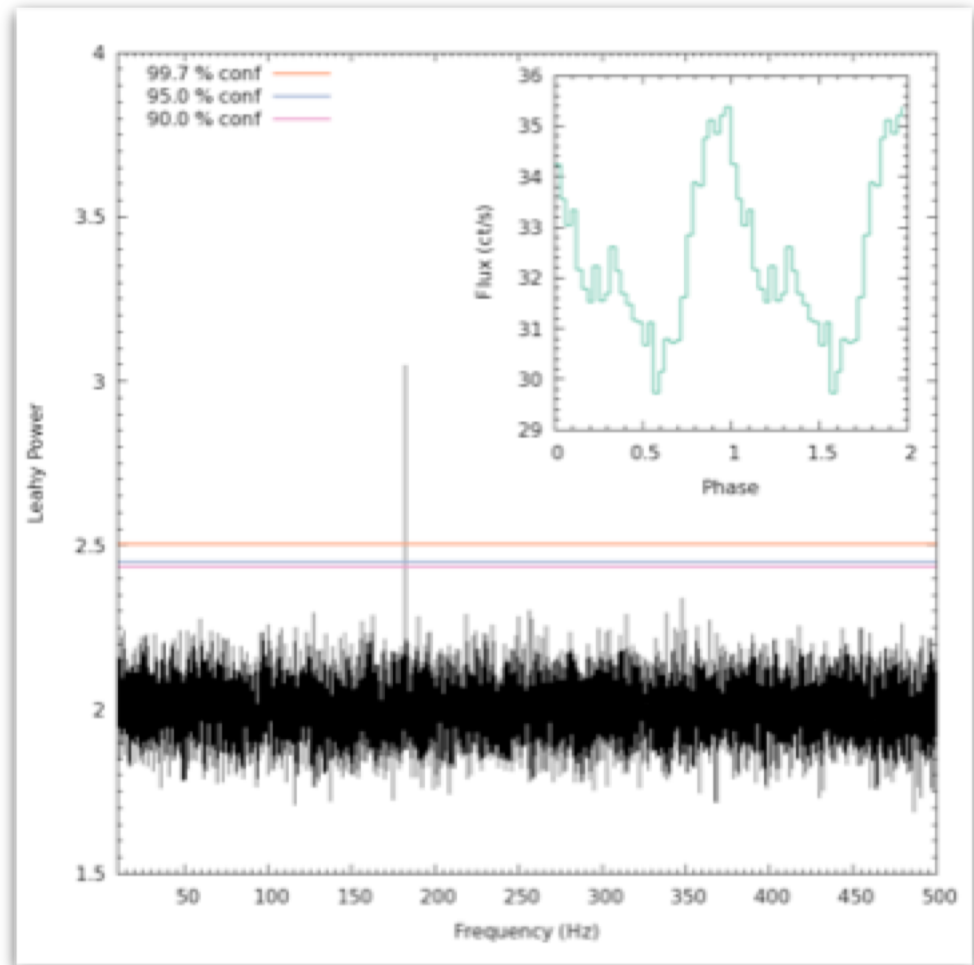
After barycenter-correcting the event times, we computed a power spectrum and detected a >5-sigma pulsation at 182.067 Hz, confirming that the active source is indeed Swift J1756.9-2508 (see Krimm et al. 2007, ApJ 668, L147, and the erratum in Krimm et al. 2009, ApJ 703, L183).

The pulsar has a known binary period of 54.7 min. Propagating the best-known orbital solution (Patruno et al. 2010, MNRAS 403, 1426) under the assumption of a constant binary period, we calculated a current-epoch time of ascending node to be $T_{\text{asc}} = \text{MJD } 58211.0170(2)$ TDB. The uncertainty on this predicted reference time is less than 0.5% of the orbital period. We then optimized our trial orbital solution by scanning a grid of T_{asc} values in steps of $1\text{E-}5$ d. We found the best solution at $T_{\text{asc}} = \text{MJD } 58211.01736$ TDB, consistent with the prediction within 2 sigma (statistical uncertainty).

Folding the data using this orbital ephemeris, we retrieved an improved pulsation detection (22 sigma) at frequency $F_0 = 182.065803(2)$ Hz. The pulse profile is non-sinusoidal, showing a fractional sinusoidal amplitude of 5.9% for the fundamental and 3.4% for the first overtone, both measured in the 1-10 keV band. The shape of the pulse profile is similar to those shown in Figure 1 of Patruno et al. (2010), albeit in a somewhat softer, overlapping energy band. A more detailed analysis is underway.

The X-ray spectrum is consistent with an absorbed disk-blackbody plus power-law model (red. $\chi^2 = 1.18$ for 840 d.o.f.). We measured an absorption column density of $N_{\text{H}} = 6.4(2)\text{E}22 \text{ cm}^{-2}$, a disk temperature of $kT = 0.17(1) \text{ keV}$, and a power-law photon index of $\Gamma = 2.04(3)$. There is no evidence of an Fe line feature near ~6.4 keV in the spectrum. The unabsorbed 1-10 keV flux is $1.3\text{e-}9 \text{ erg/s/cm}^2$. All values are consistent with those of the previous outbursts, and suggest that the source is in a typical atoll-type island (hard) spectral state.

Further NICER observations of this source are underway. Additional multiwavelength follow-up is encouraged.





Two recent Astronomer's Telegrams (cont.)

Discovery of the accreting pulsar in IGR J17379–3747

NICER discovers millisecond pulsations from the neutron star LMXB IGR J17379-3747

ATel #11507; *T. E. Strohmayer (NASA/GSFC), P. S. Ray (NRL), K. C. Gendreau (NASA/GSFC), P. M. Bult (NASA/GSFC), S. Guillot (IRAP, CNES), S. Mahmoodifar (NASA/GSFC), G. K. Jaisawal (DTU Space), Z. Arzoumanian (NASA/GSFC), D. Altamirano (Univ. of Southampton), S. Bogdanov (Columbia), D. Chakrabarty (MIT), T. Enoto (Kyoto Univ.), C. B. Markwardt (NASA/GSFC), F. Özel (Univ. of Arizona), S. M. Ransom (NRAO)*

on 6 Apr 2018; 02:22 UT

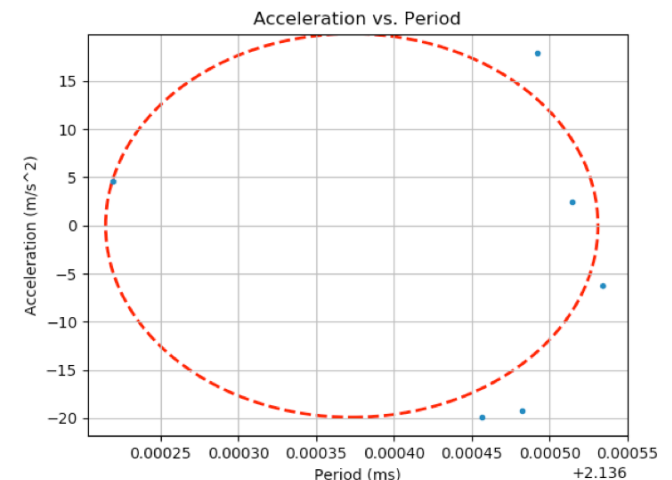
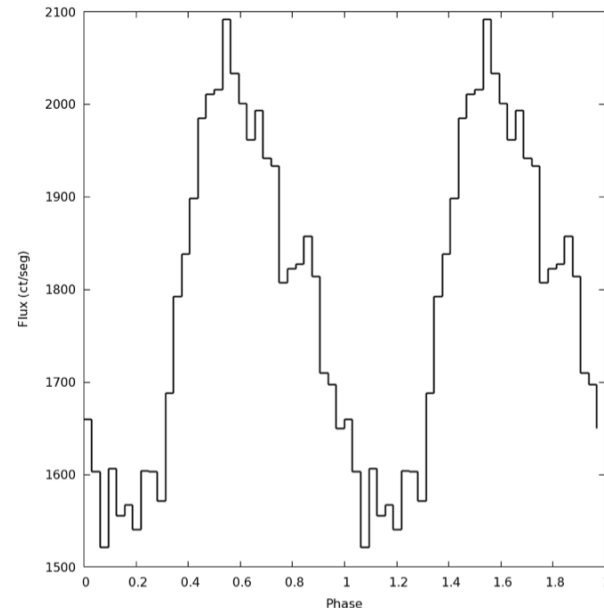
Credential Certification: Tod Strohmayer (tod.strohmayer@nasa.gov)

Subjects: X-ray, Request for Observations, Binary, Neutron Star, Pulsar

Referred to by ATel #: [11520](#)

Tweet

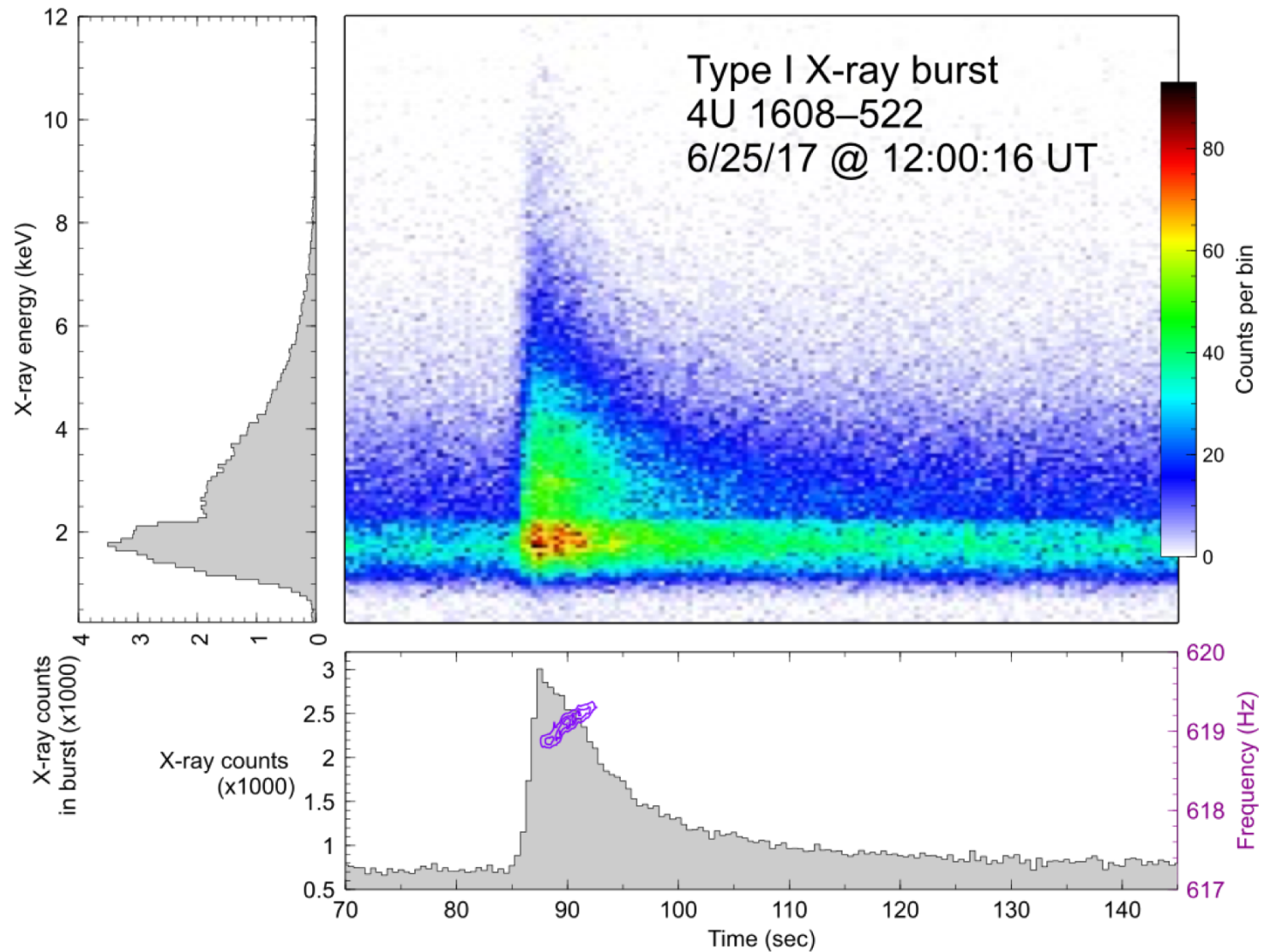
Following a 2018 March 19 MAXI alert of a new outburst of the neutron star low-mass X-ray binary IGR J17379-3747 (ATel #11447), NICER has observed the source daily since 2018 March 29. From that date onward, the mean count rates detected each day through April 1 were 12.9, 11.0, 8.7, and 4.7 ct/s (0.5-12 keV), respectively. The background count rate in this band is less than 1 ct/s. After applying barycenter corrections to the event times using the radio position reported in ATel #11487, we computed a combined power spectrum of the full ~9 ks collected exposure and detected a clear pulsation (> 7 sigma significance for a single trial) at a frequency of 468.05 Hz. The data consist of 11 segments of varying uninterrupted exposure between 500 s and 1000 s duration. We searched these segments for pulsations individually using the PRESTO acceleration search code. We detected a power-spectrum excess near 468.05 Hz in seven of those segments (at a significance ranging from 6 to 8 sigma in each segment, with frequencies ranging from 468.05 to 468.12 Hz). Fitting the observed frequency modulation with a circular orbit model yielded an excellent fit, with an orbital period of 1.88 hrs and a minimum companion mass of 0.055 Msun (assuming a 1.4 Msun neutron star). The barycentric pulsar spin frequency is 468.0832 Hz. We extracted a 0.5-10 keV spectrum for each day, and find they are all consistent with an absorbed power-law model. However, adding a blackbody component significantly improves the fits (reduced $\chi^2 = 0.97$ for 1278 d.o.f.). The blackbody temperature decreases from 0.52 ± 0.06 keV to 0.39 ± 0.03 keV as the flux declines. At the same time, the power-law component softens slightly, with the photon index evolving from 2.1 ± 0.1 to 2.4 ± 0.1 . The measured hydrogen column density is $N_H = (0.7 \pm 0.1) \times 10^{22} \text{ cm}^{-2}$, consistent with a previously reported value (ATel #1714), but significantly lower than the most recently reported value (ATel #11487). The unabsorbed flux decreases from $7.4 \times 10^{-11} \text{ ergs/cm}^2/\text{s}$ (2018 March 29) to $2.5 \times 10^{-11} \text{ ergs/cm}^2/\text{s}$ (2018 April 1). Our pulsation detection conclusively identifies IGR J17379-3747 as an accreting millisecond X-ray pulsar. NICER monitoring of the source continues. Given its rapidly declining X-ray flux, prompt follow up at other wavelengths is encouraged.





Early NICER burst results (cont.)

619 Hz burst oscillations

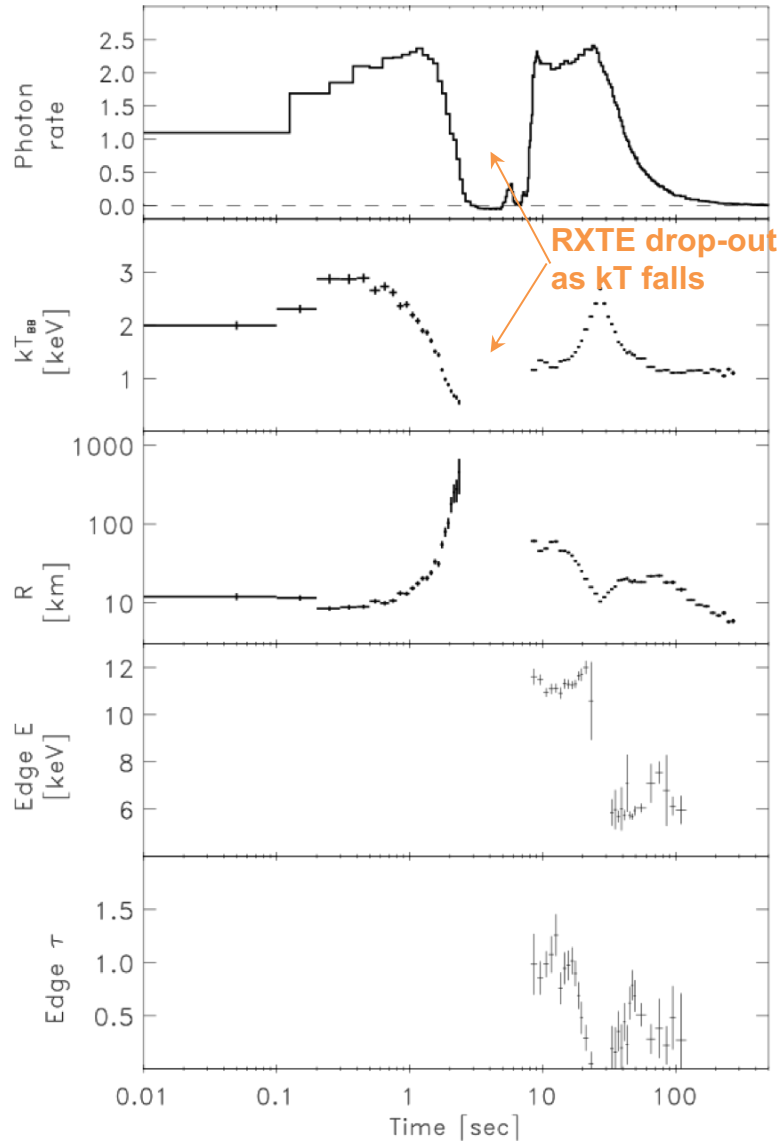




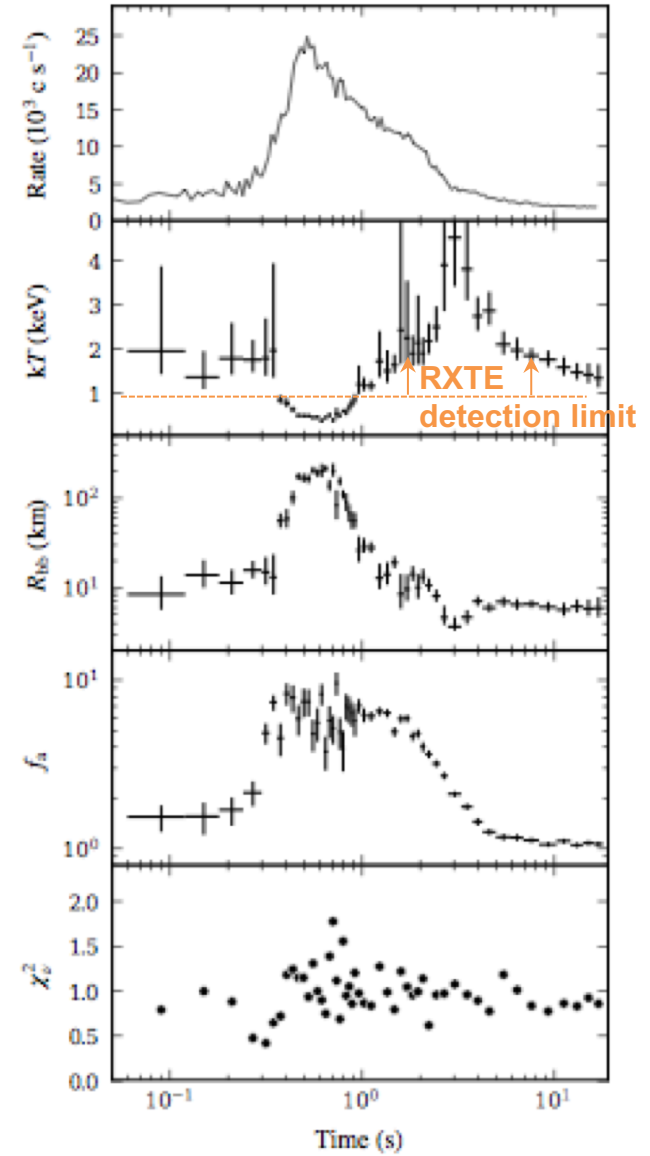
Early NICER burst results

Photospheric radius “super expansion” evolution

4U 1722–30 with RXTE



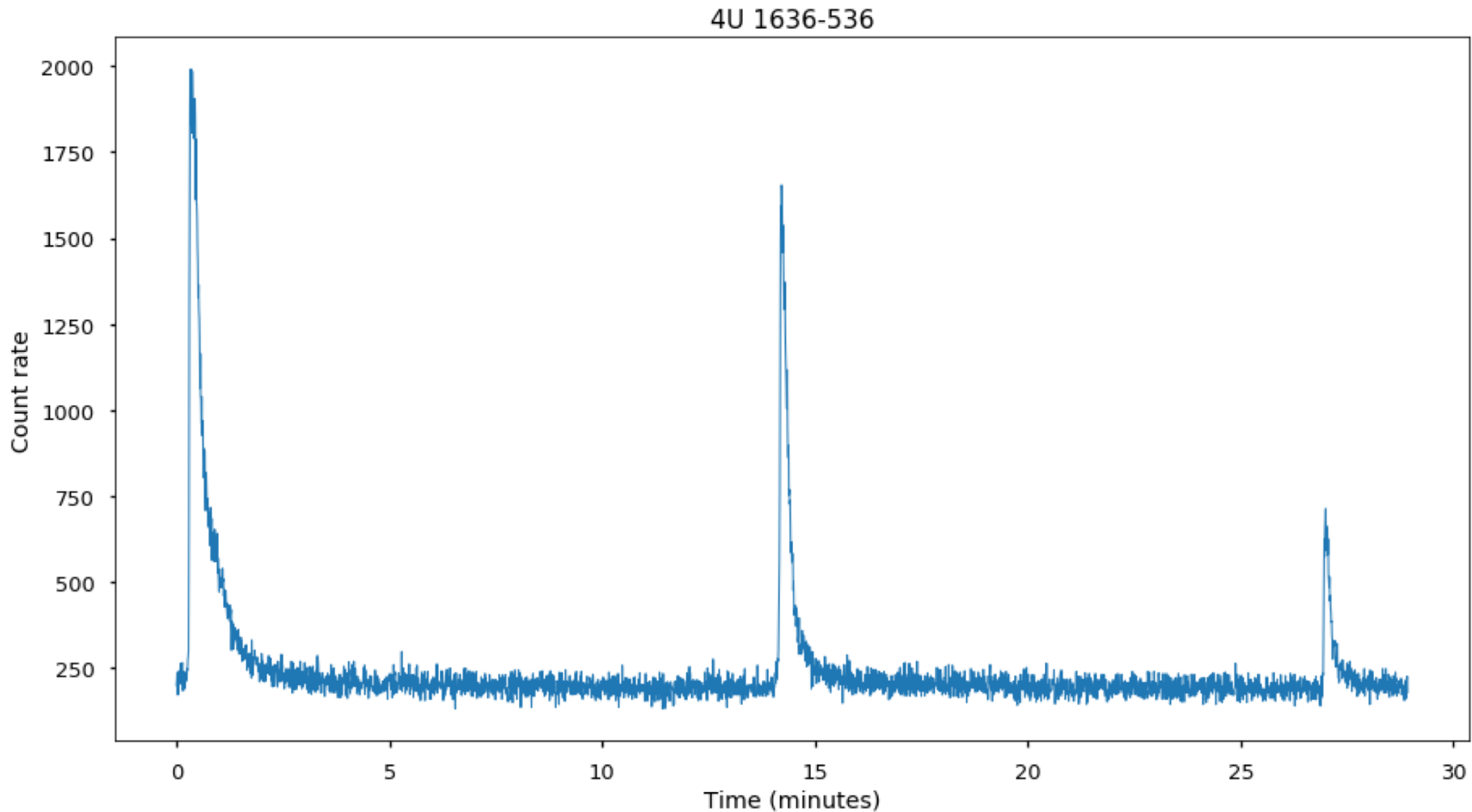
4U 1820–30 with NICER





Short recurrence-time bursts

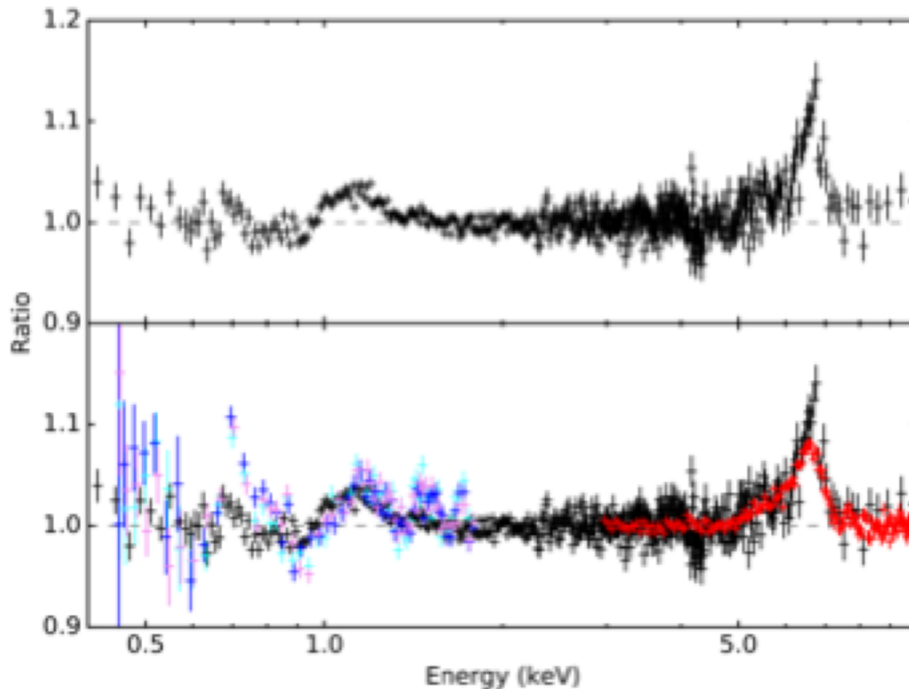
Just 13 min apart, too soon for the atmosphere to recover...



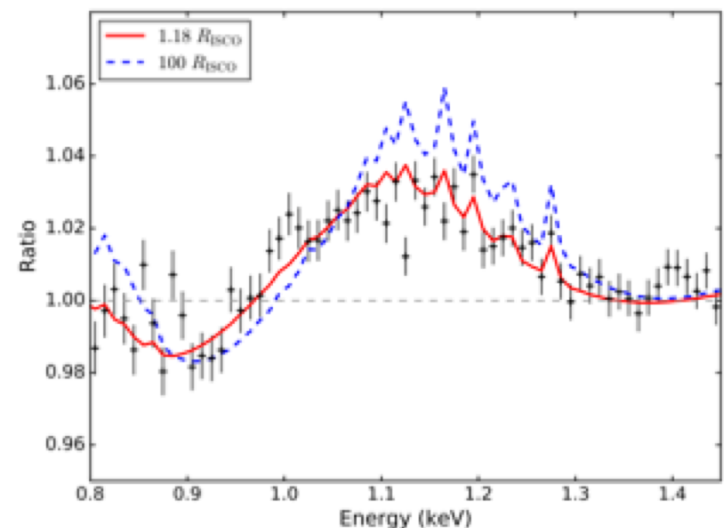
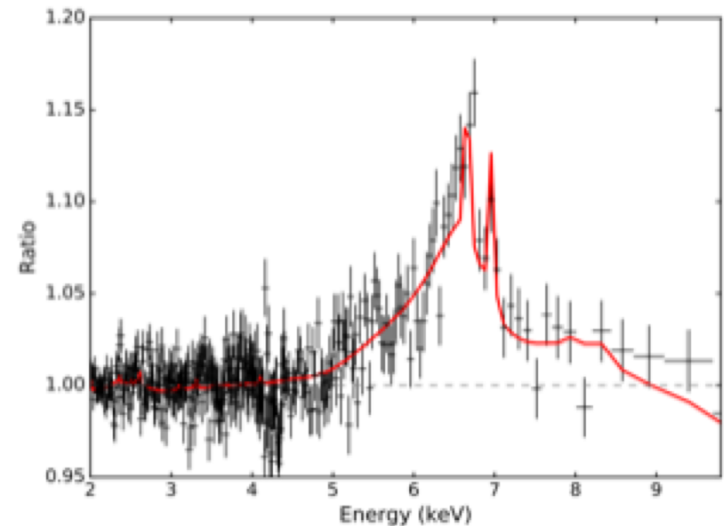


Iron “reflection” in Serpens X-1

Inner edge of accretion disk is upper limit on NS radius



NICER (black), NuSTAR (red), XMM-Newton (blue/purple)

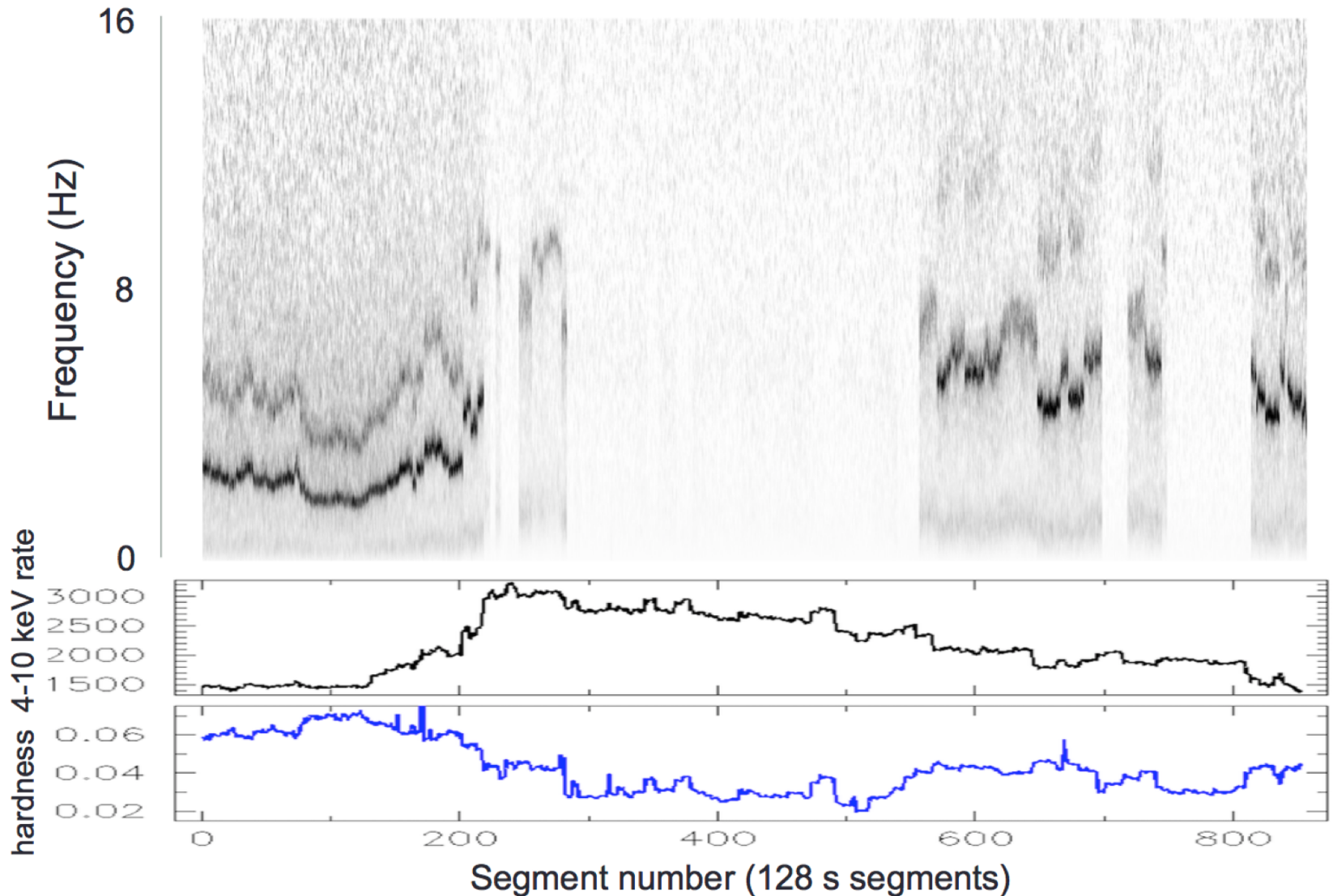


Reflection lines are shaped by Doppler and relativistic effects due to the proximity to the neutron star. In a 4.5 ksec observation the best-fit reflection models suggest that the inner disk extends close to an inner radius of between 12.4 and 19.8 km.



NICER Observatory Science results

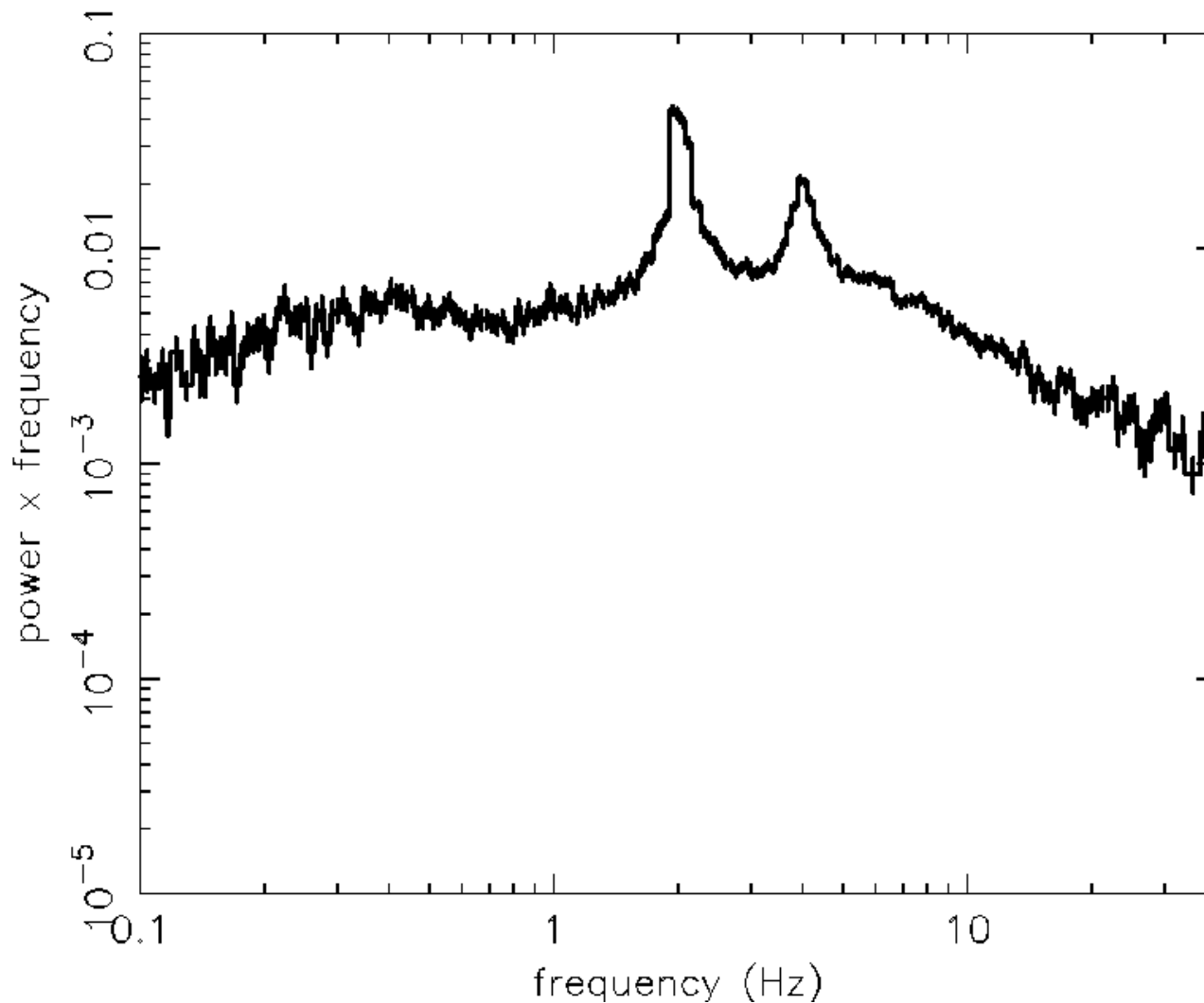
Black hole transient in outburst: MAXI J1535–571





NICER Observatory Science results (cont.)

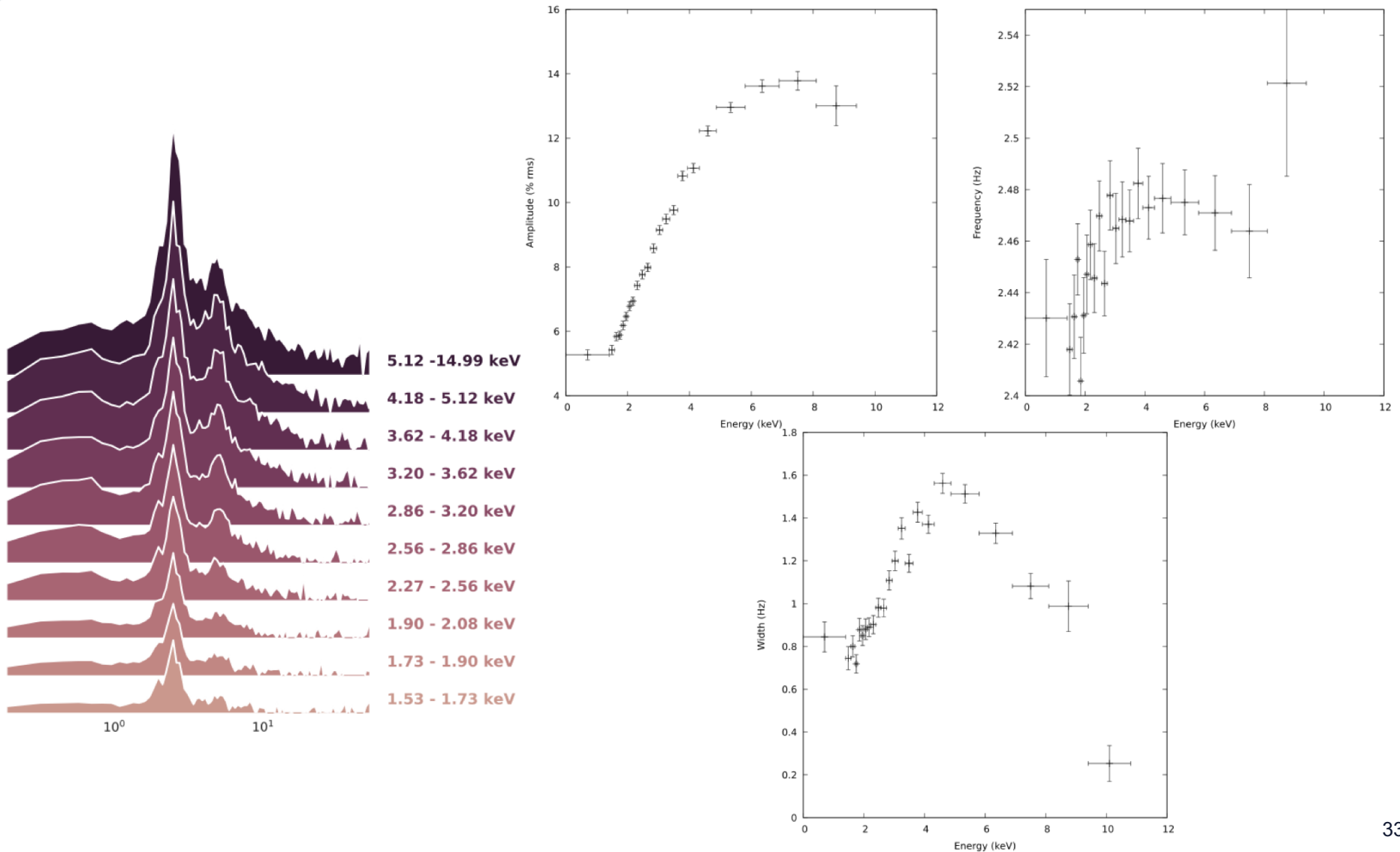
MAXI J1535's marching QPOs





Early black-hole binary results (cont.)

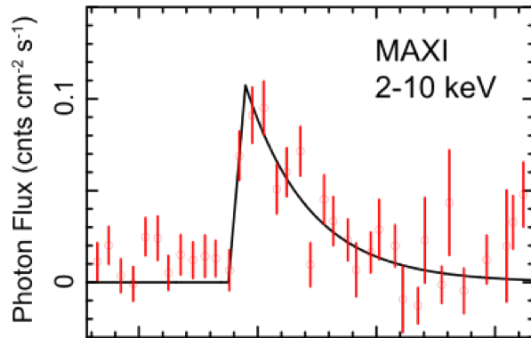
Energy dependence of low-frequency QPOs in MAXI J1535-571



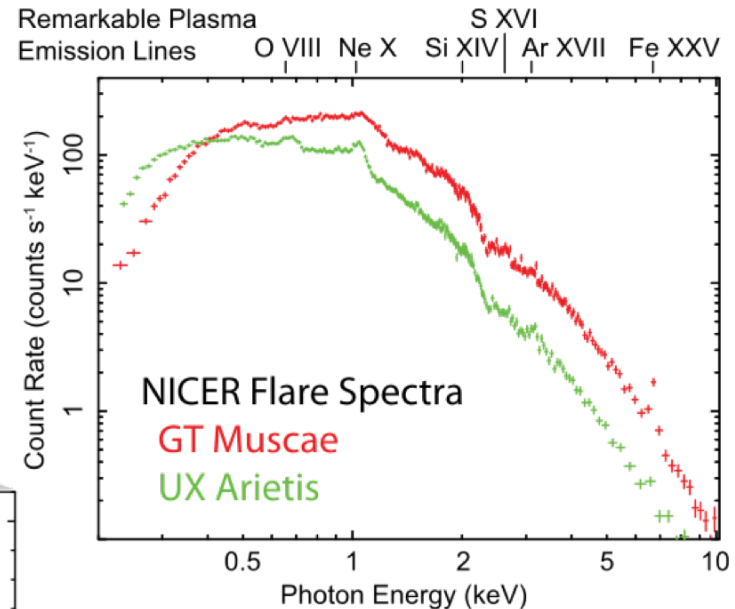
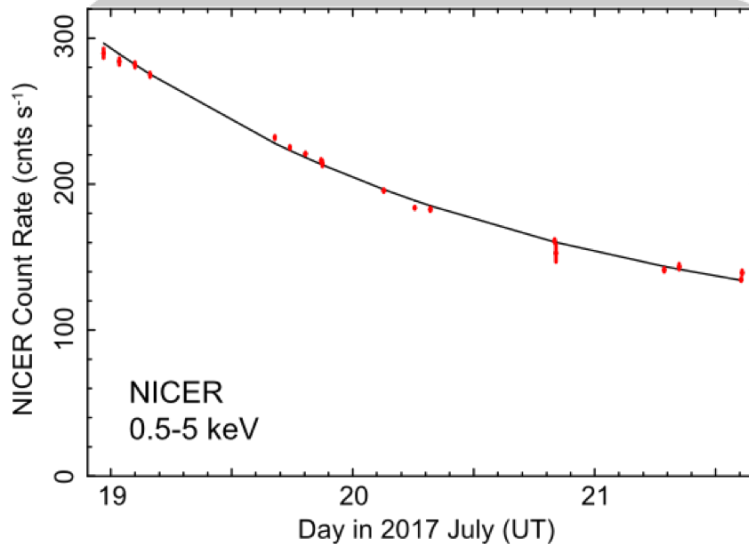


NICER Observatory Science results (cont.)

Two stellar flare ToOs triggered by MAXI: GT Mus and UX Ari



GT Muscae Flare Light Curve



Constraints on elemental composition of flaring plasma, and stellar magnetic structure, on previously inaccessible timescales

MAXI has just been extended for another 3 years!

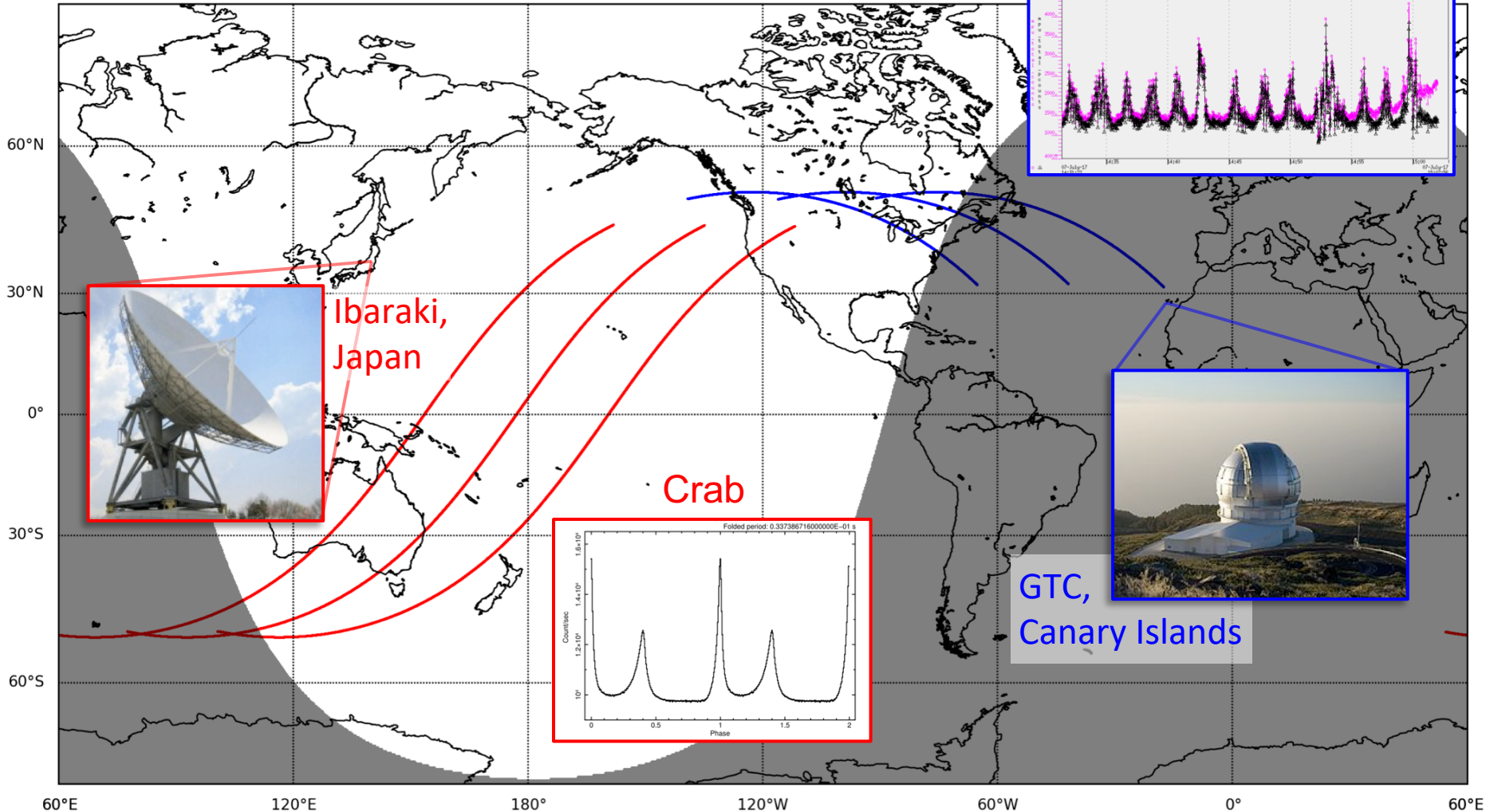


Coordination across facilities and wavelengths

Two targets, two ground-based telescopes, three successive ISS orbits

GRS 1915+105

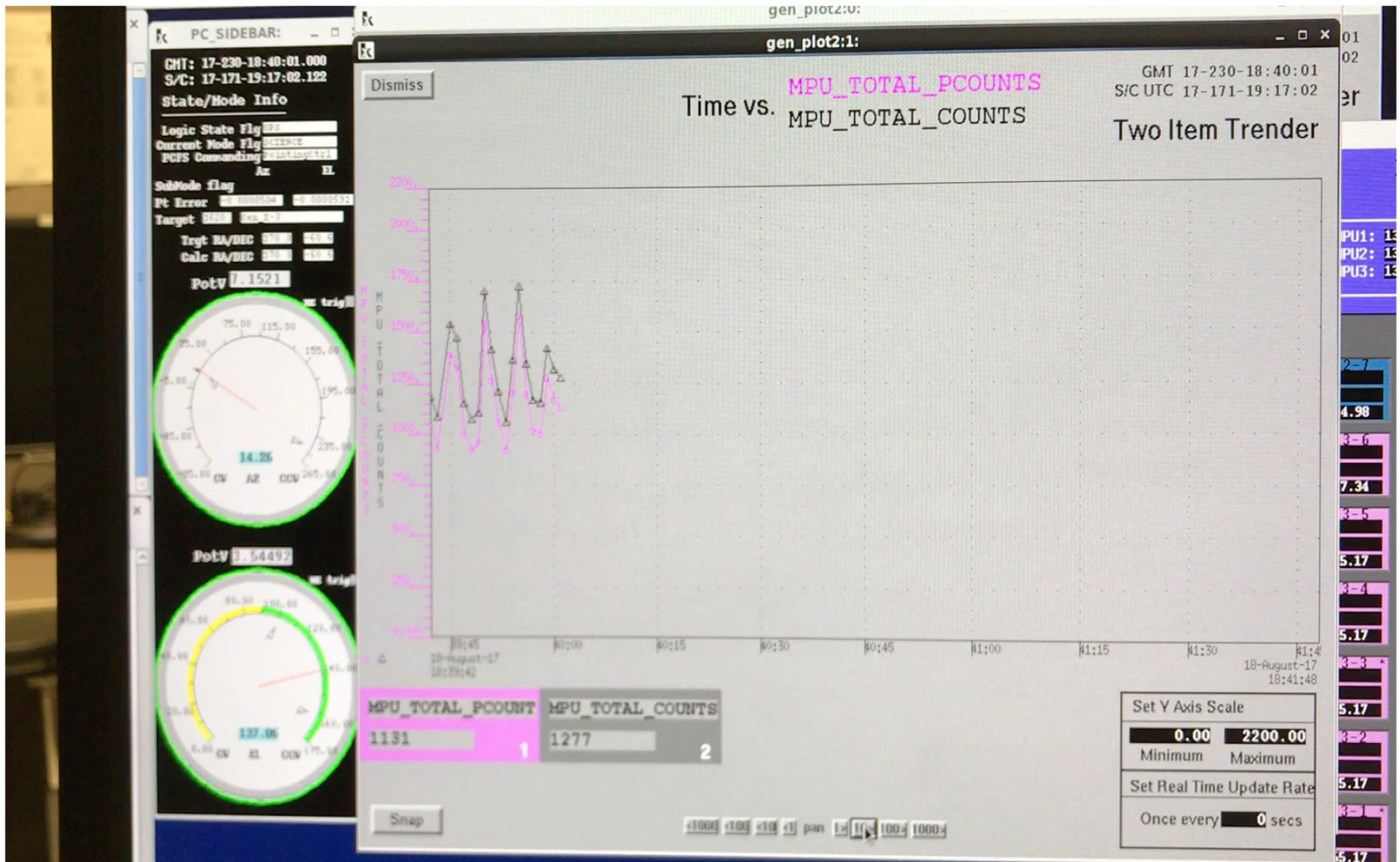
Coordinated Crab & GRS 1915+105, 2017 Aug 9-10





Live ISS telemetry ~80% of the time

Cen X-3 pulsations in real time

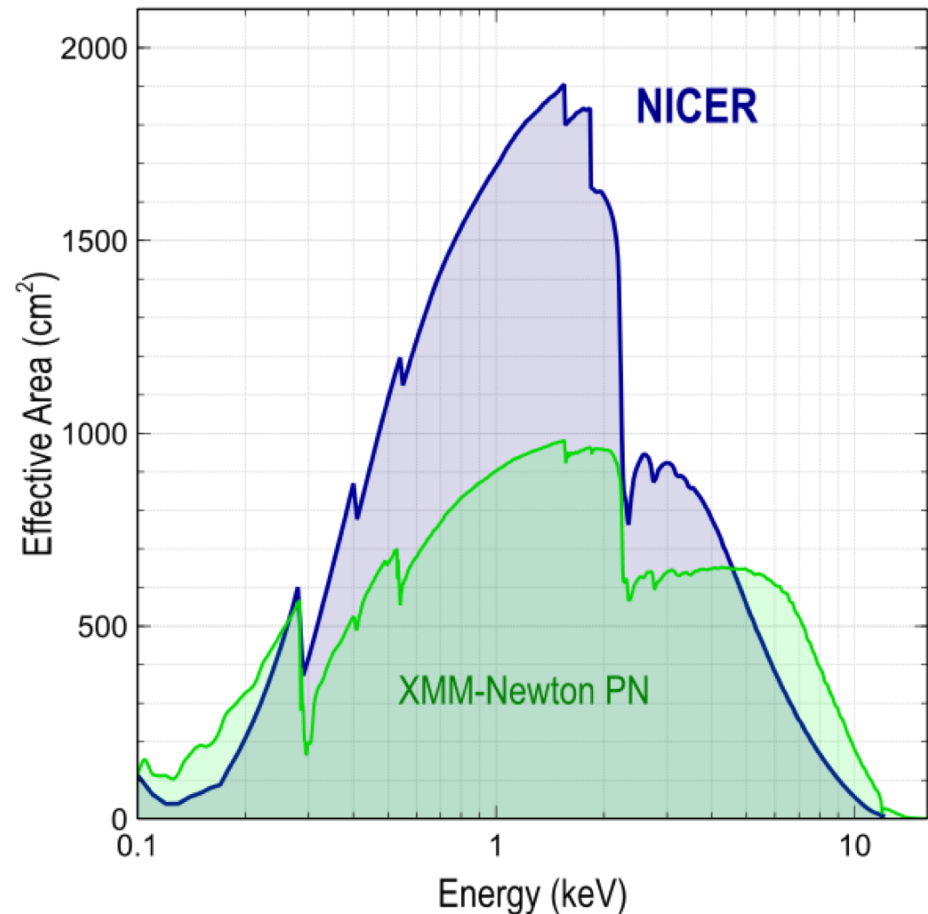




X-ray Timing Instrument (XTI) capabilities

A novel combination of sensitivity, timing, and energy resolution

- Spectral band: 0.2–12 keV
- Timing resolution: < 100 nsec RMS absolute
- Energy resolution: 140 eV @ 6 keV
- Non-imaging FOV: 6 arcmin diameter
- Background: < 0.5 cps
- Sensitivity, 5σ : 1×10^{-13} erg/s/cm²
 - 0.5–10 keV, 10 ksec (Crab-like)
 - $\sim 3\times$ better than XMM-Newton's timing capability (PN clocked)
- Max countrate: $\sim 38,000$ cps (3.5 Crab)
 - Deadtime accounted for in telemetry

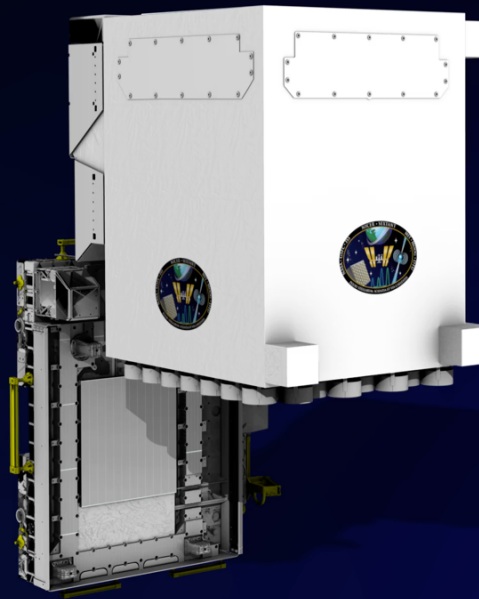




The NICER Payload

NICER

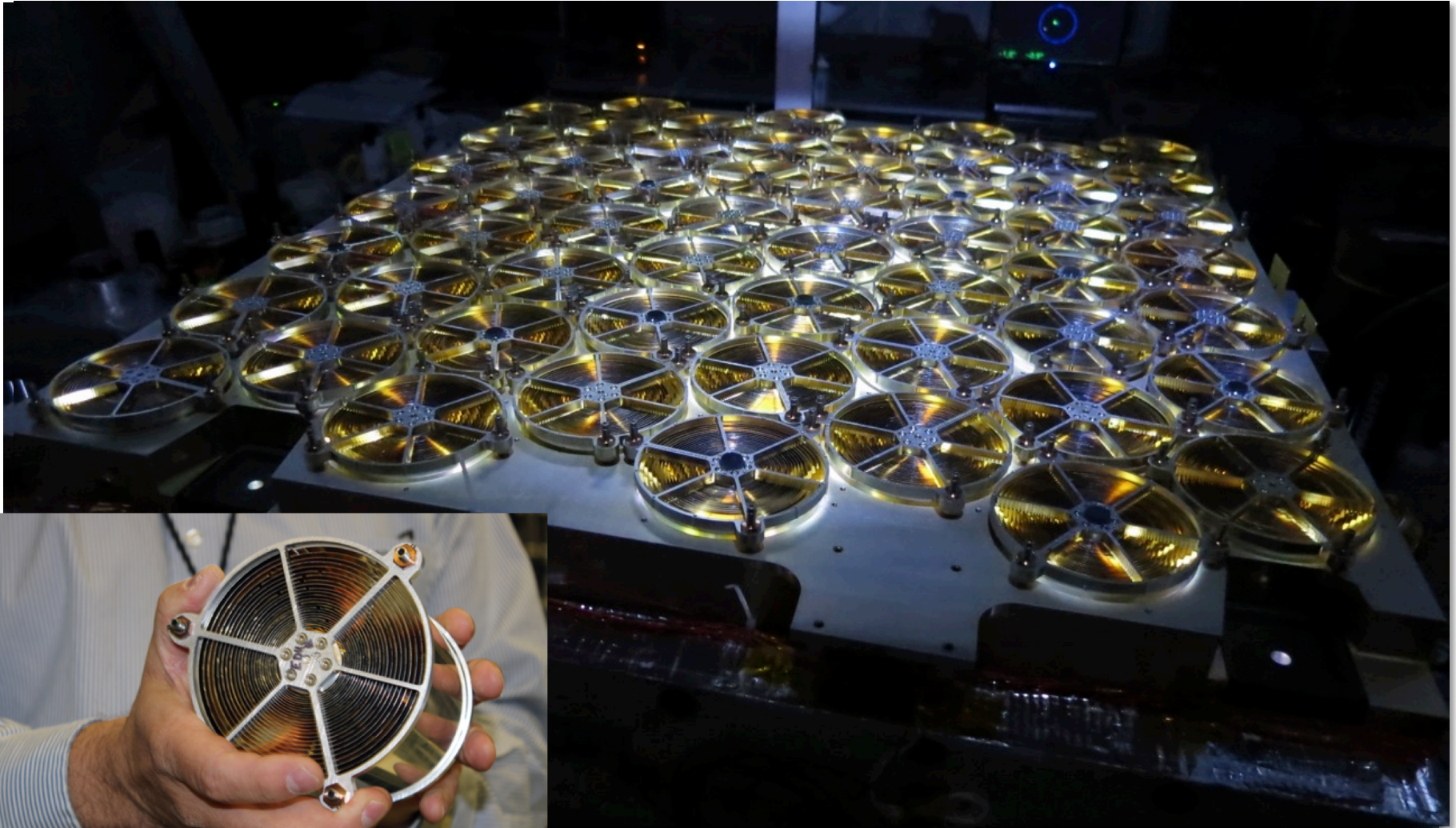
Neutron Star Interior Composition Explorer





X-ray Concentrator optics

Single reflection, grazing-incidence nested gold-coated Al foils





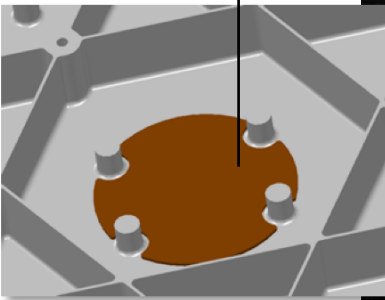
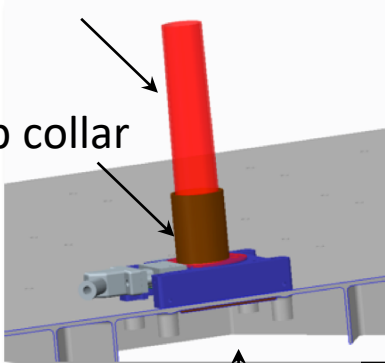
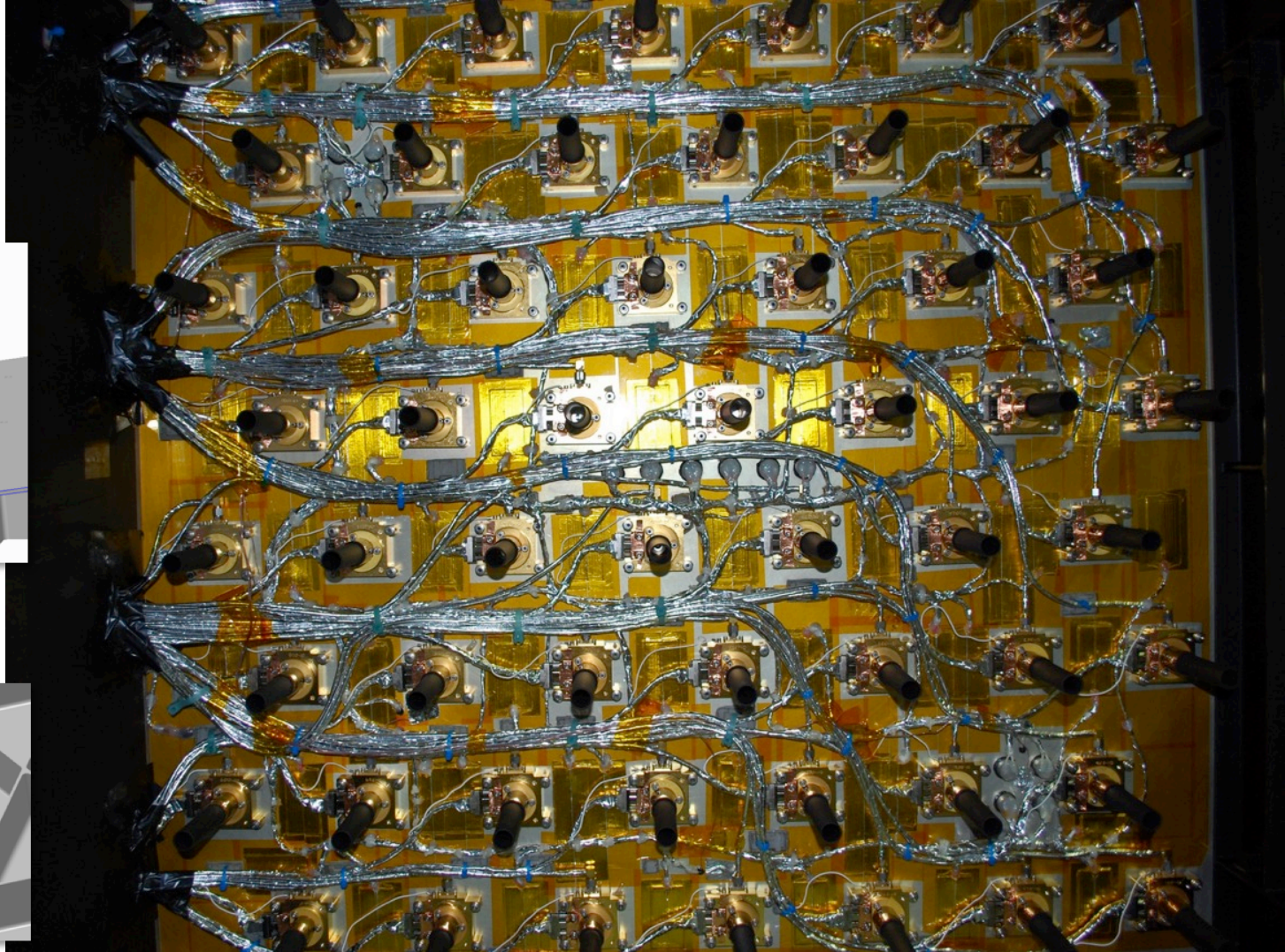
Detector plate

*Radiation
shielding*

Au/Ag “traffic cone”

Pb collar

Pb disk





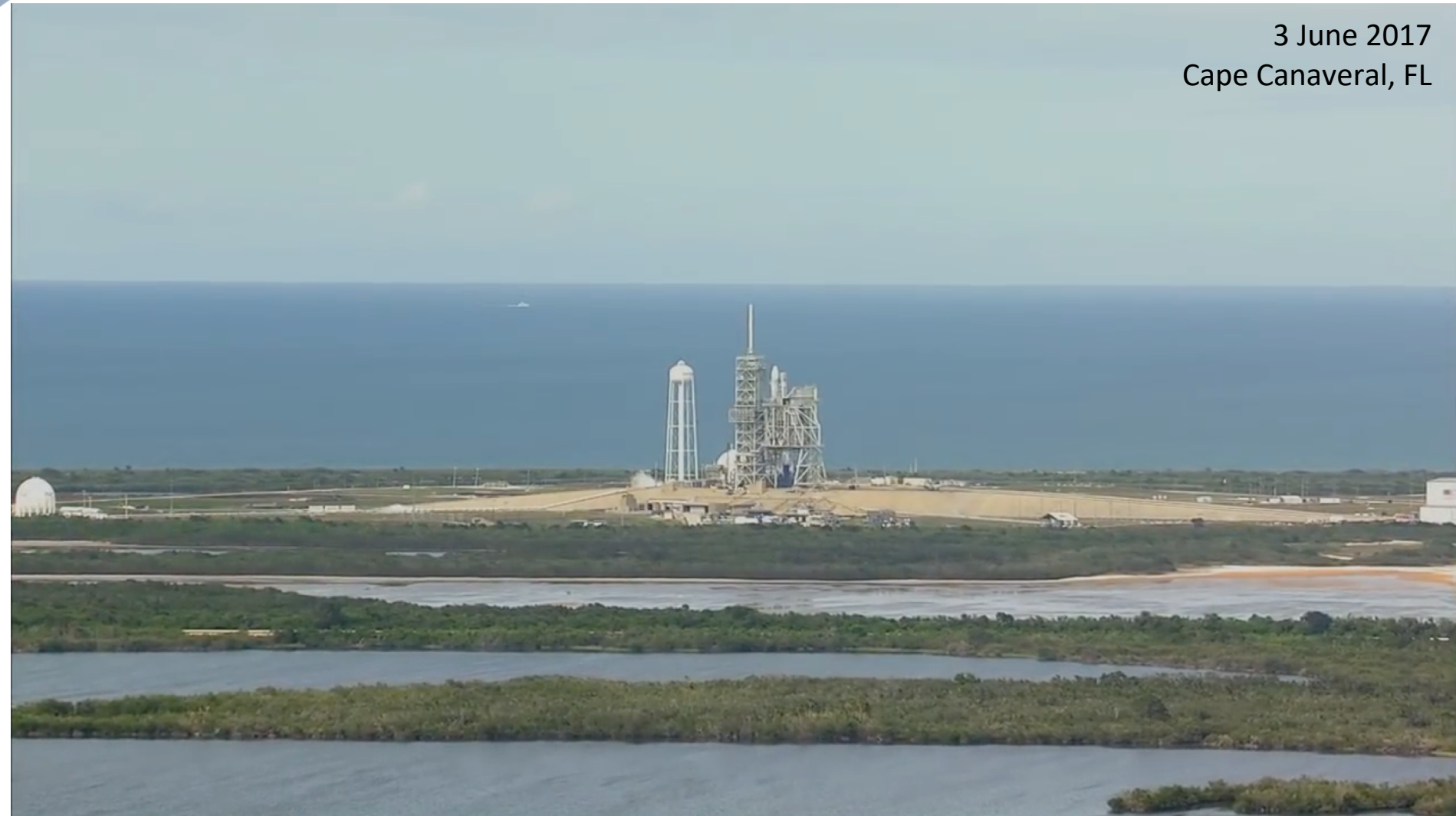
NICER's ready to go!





Launch!

3 June 2017
Cape Canaveral, FL





Transport and installation (cont.)

Dragon and NICER proceed to ISS transfer orbit





Transport and installation (cont.)

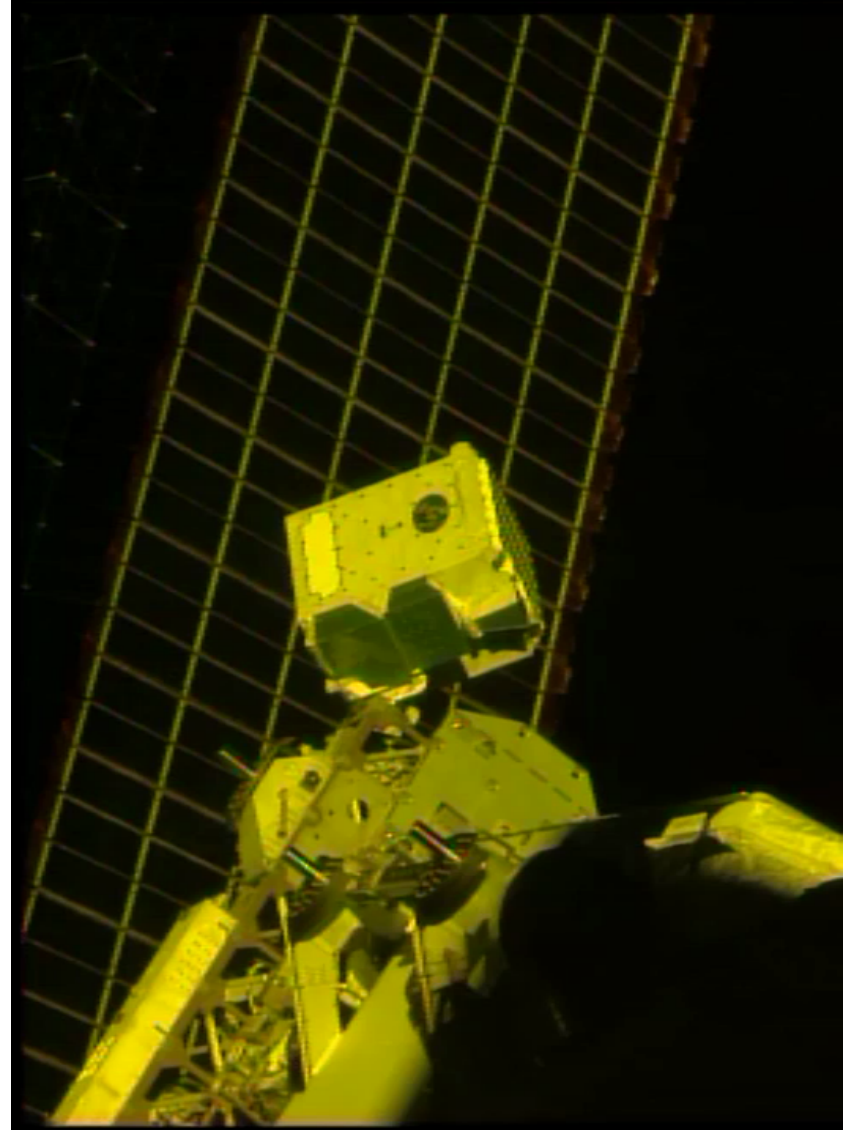
Extraction from Dragon was delicate...





Watch *NICER* collect your photons!

Occasional / on-demand live ISS video





Baseline Science and GO timeline

- **3 Jun 2017** — Launch
- **14 Jun 2017** — Activation
- **17 Jul 2017** — Beginning of Baseline Science ops
- **Fall 2017** — Establishment of NICER GOF; PI discretionary time requests considered
- **Feb 2018** — Release of NICER GO Cycle 1 call for proposals (ROSES), *observations contingent on mission “bridge” extension*; currently, no funding or data rights for GOs
- **March 2018** — **First public data release** to HEASARC
- **Jun 2018** — Mission Success Progress Review
- **Sept 2018** — Cycle 1 proposals due
- **Jan 2019** — End of Baseline Science mission; beginning of Cycle 1 GO observations *if mission bridge is approved*.
- **Spring 2019** — Consideration of NICER mission extension by Astrophysics Senior Review
- **Summer 2019** — Senior Review results announced
- **Oct 2019** — Bridge & GO Cycle 1 complete, possible 3-yr extension



Guest Observer Program

NICER tools at HEASARC available to anticipate observations of your favorite targets

- Timing-spectral studies of black-hole binaries & AGN
- Broadened iron lines
- Coronal emission from stars, other soft transients
- ... and more!

The Neutron star Interior Composition Explorer Mission

The Neutron star Interior Composition Explorer (NICER) is a proposed NASA Explorer Mission of Opportunity dedicated to the study of the extraordinary gravitational, electromagnetic, and nuclear-physics environments embodied by neutron stars. NICER will explore the exotic states of matter inside these stars, where density and pressure are higher than in atomic nuclei, confronting theory with unique observational constraints. NICER will enable rotation-resolved spectroscopy of the thermal and non-thermal emissions of neutron stars in the soft (0.2-12 keV) X-ray band with unprecedented sensitivity, probing interior structure, the origins of dynamic phenomena, and the mechanisms that underlie the most powerful cosmic particle accelerators known. NICER achieves these goals by deploying, following launch in late 2016, an X-ray timing and spectroscopy instrument as an attached payload aboard the International Space Station (ISS). Grazing-incidence optics coupled with silicon drift detectors, actively pointed for a full hemisphere of sky coverage, will provide photon-counting spectroscopy and timing registered to GPS time and position, with high throughput and relatively low background.

In addition to advancing a vital multi-wavelength approach to neutron star studies through coordination with radio and γ-ray observations, NICER will provide a rapid-response capability for targeting of transients, continuity in X-ray timing astrophysics investigations post-RXTE through a proposed Guest Observer program, and new discovery space in soft X-ray timing science.

Simulated NICER count rates and spectra can be derived using the [WebPIMMS](#) and [WebSPEC](#) tools.

WebPIMMS
A Mission Count Rate Simulator
Powered by PIMMS v4.6a

Access the multiple component model [interface](#).

Convert From: Flux Into: NICER

Examples of Common FLUX Input/Output Ranges

Input Energy Range (low-high): 2-10 keV Units

Output Energy Range (low-high): default keV Units

Source: Flux / Count Rate 2e-8 (erg/cm²/s) (counts/s)

Galactic nH 3e21 (cm⁻²) Redshift none Intrinsic nH none (cm⁻²)

Model of Source: Power Law Model Parameters: Photon index 2.1

Black Body keV

Therm. Processes kT

WEBSpec

WebSpec is a web interface for the X-ray spectral fitting package, [XSPEC](#). It simulates spectral data for a variety of X-ray missions/instruments. WebSpec can not be used to analyze real data. This page is for the simple interface. More experienced XSPEC users, may want to use an [advanced interface](#) which allows up to 9 components.

Latest News:
12/14/12 Updated for Chandra CY-15.
10/3/12 Updated XIS matrices for Suzaku AO-8.

Choose a Mission/Instrument: NICER

Specify the desired model expression by clicking on a model in each of the scroll boxes and indicating via the checkbox whether you want pileup and/or photoelectric absorption. If you only want one model then click on the top blank line in the second scroll box. When you are ready click the button to set model parameters. To start again click the reset button.

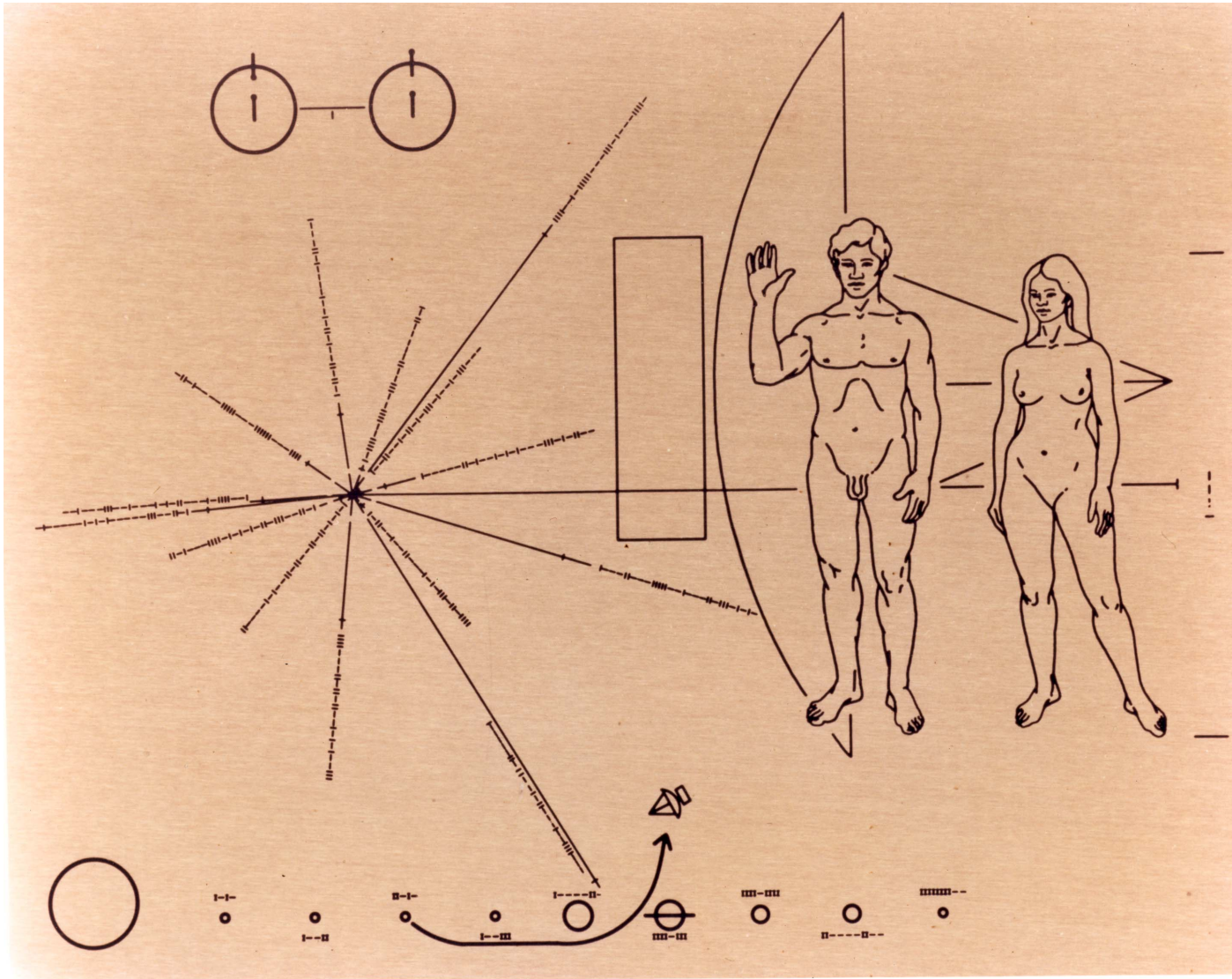
Pile-up: ☐ Photoelectric Absorption: ☒ X + Available Models: Black Body, Power Law, Broken Power Law, Power Law with cutoff, Gaussian, Disk Line Emission, APEC, BAPEC

I'm ready to set model parameters Reset all fields



SEXTANT — Heritage

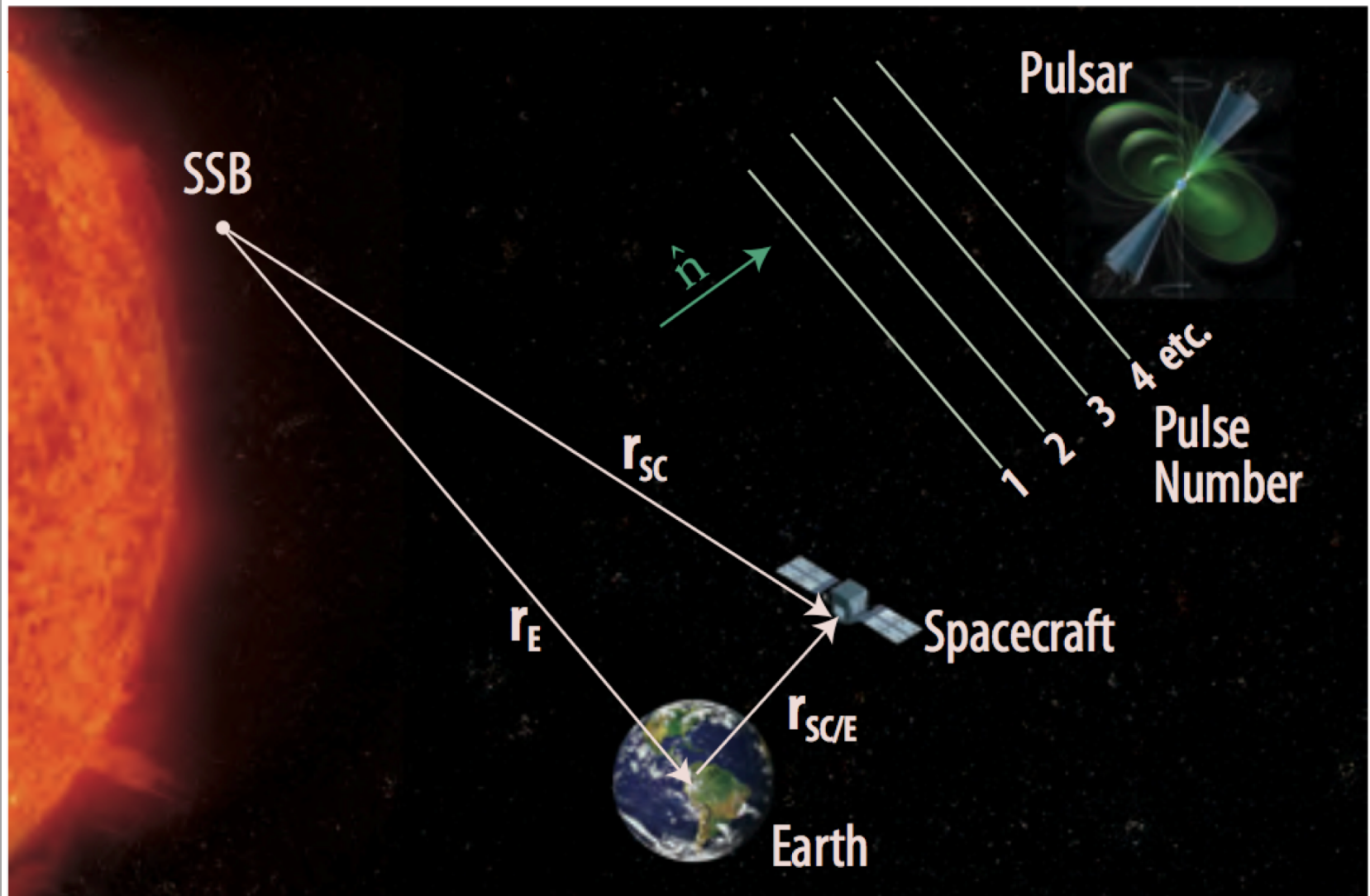
Pioneer Plaques and Voyager Records





SEXTANT — Method

Inverting traditional pulsar-timing techniques





SEXTANT — Deep-space navigation

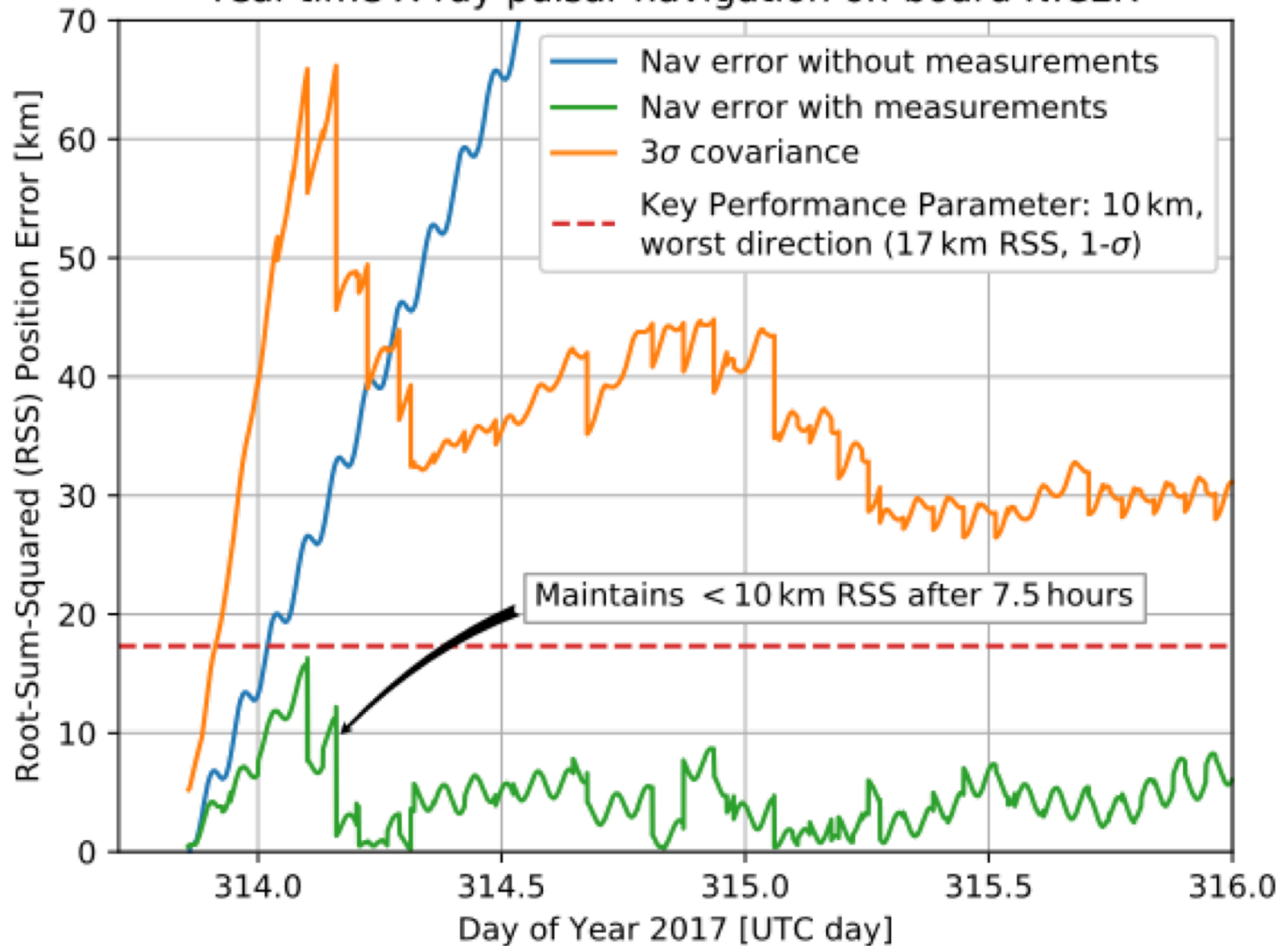
Objectives:

- Demonstrate GPS-like navigation anywhere in the Solar System using X-ray observations of millisecond pulsars (MSPs)
- Provide *first real-time, on-orbit demo* of X-ray pulsar-based navigation (XNAV)
 - Key Performance Parameter: better than 10 km worst-direction orbit determination in less than 1 week
 - Stretch Goal: better than 1 km in less than 2 weeks
- Determine practical limitations of XNAV
- Catalog and characterize additional “beacon” MSPs
- Assess the feasibility of pulsar-based time transfer and timescale



Success!

SEXTANT successfully demonstrates fully autonomous, real-time X-ray pulsar navigation on-board NICER





Observing the sky from ISS

Sim Time 1070 Sun Angle 81°
 Latitude -23° 57' 39" Moon Angle 96°
 Longitude 97° 06' 06"
 RA_J 07h 48m 33.8s
 Dec_J -67° 45' 7"

Command Sequence

```

0000 [Slew to] EXO 0748-676
0130 [Track]  EXO 0748-676
1140 [Slew to] PSR J0030+0451
1250 [Track]  PSR J0030+0451
3060 [Slew to] PSR J1809-2332
3180 [Track]  PSR J1809-2332
4380 [Slew to] T0011.868+10.321
4630 [Track]  T0011.868+10.321
  
```



Star Tracker FOV

